Investigation of Environmental Impacts on Piezoelectric Weigh-In-Motion Sensing System

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Transportation by trucks plays a major role in North America's economy. The growth of this industry will increase the loads on existing roads and highways and raises the possibility of overloaded vehicles, which causes significant damage to the pavement and consequently will reduce the lifespan of the roads. Weigh-in-motion (WIM) systems technology helps to address the challenge of overloaded vehicles. This technology provides traffic monitoring, collects data for pavement research and design, and improves the capacity of static weigh station operations. However, there is still a lack of knowledge about the behaviour of WIM sensors installed in different environments, which affects reliable and precise data gathering. More knowledge is required on proper installation procedures, pavement design for WIM systems, choice of sensor type for location, and calibration processes. This research is intended to explore the behaviour of WIM piezoelectric sensors under different loads and environmental conditions. Specifically, the effects of air and pavement temperature, and weight and speed of trucks are examined with respect to the estimation accuracy of WIM sensors. To accomplish this, three WIM systems composed of different piezoelectric transducers were installed at the CPATT test site at the Waste Management facility of the Region of Waterloo in 2007, and two WIM systems were installed between exits 238 and 250 on Highway 401 eastbound near Woodstock, Ontario. It was concluded that the output of the polymer piezoelectric sensor is influenced by temperature and weight factors but not by normally observed vehicle speed differences. While temperature can be compensated for, not enough information has been gathered yet does the same for weight factor. It should be noted that very low speeds (e.g. < 50 km/hr) result in significant errors for all the sensors, so that in congested sections WIM results should be interpreted accordingly. These results will be useful for investigating the effects of environmental conditions on other WIM systems and for predicting the responses of sensors in actual installation environments. This will assist in the recommendation of: (1) alternative and transparent calibration procedures for the WIM sensor systems, (2) and improved benefits of least expensive technology.

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Table of Contents

Author's Declaration ii
Abstract iii
Acknowledgements iv
Table of Contents v
List of Figures viii
List of Tables xi
Chapter 1 Introduction 1
1.1 Motivation 2
1.2 Problem Statement 2
1.3 Background and Review 4
1.4 Objectives of the Research 5
1.5 Scope of the research 5
1.6 Methodology 6
1.7 CPATT's Pavement Testing Facilities 8
1.7.1 The Landfill Site 8
1.7.2 The Highway 401 Site 8
1.8 Organization of the Thesis 8
Chapter 2 Literature Review 10
2.1 Introduction 10
2.2 Weigh-In-Motion Sensor 10
2.3 Types of Weigh-In-Motion Systems 12
2.3.1 Bending Plate WIM System 12
2.3.2 Load Cell WIM System 12
2.3.3 Piezoelectric WIM System 12
2.4 Cost Comparisons 16
2.5 Factors Affecting WIM Sensors Accuracy 19
2.6 Review of Research in Weigh-In-Motion 21
2.6.1 WIM Research in North America 21
2.6.2 WIM Research in Europe 22
2.7 Pavement Smoothness Specification for WIM 23
2.8 Modeling the WIM Sensors and the Flexible Pavements 25

2.8.1 Efforts on Sensor-Pavement Modeling and Verification 25
2.9 Investigations on Effects of Environment on WIM Sensors' Performance 32
2.10 Modeling Factors Affecting WIM Sensors and Auto-Calibration Procedures 33
2.11 Summary and Discussion of Research Needs 41
Chapter 3 Methodology 42
3.1 Preliminary Stage 44
3.1.1 Sensor and Equipment Procurement 44
3.1.2 Installation of WIM Sensors 44
3.1.3 Calibration 53
3.2 Manual Calibration Sheets 62
3.3 Matching data from the Static Scale and WIM Stations at the Landfill Site 64
3.4 Static Scale Analysis of Weights for Heavy Trucks at the Landfill site 64
3.5 Piezoelectric WIM Sensor Raw Signal at the Landfill Site 66
3.5.1 The Quartz and Polymer Piezoelectric Sensors Output Signal at the Landfill Site 66
Chapter 4 Weigh-In-Motion Data Analyses 69
4.1 Introduction 69
4.2 Piezoelectric WIM Sensors' Performance at the Landfill Site 69
4.2.1 The Effect of Air Temperature on Performance of the WIM Sensors 73
4.2.2 The Effect of Transverse Location of Axle Loads on the Sensors' Performance 78
4.2.3 The Effect of Vehicle Speed on Performance of the WIM Sensors 81
4.2.4 The Effect of Vehicle Speed on Performance of the Newly Calibrated Sensors 84
4.2.5 Recalibration Results 86
4.2.6 Conclusions and Recommendations 87
4.3 Performance of Sensors under Typical Traffic Stream 90
4.3.1 Load Spectra at the WIM Sites 91
4.3.2 Investigations on Axle Weights of Classes 6 and 9 at the Highway 401 Site 93
4.3.3 Sensor Performance in Different Weight Categories at the Highway 401 Site 94
4.3.4 Effect of Weight Factor on Polymer Piezoelectric Sensors at the Highway 401 Site 95
4.3.5 Effect of Weight Factor on Different WIM Sensors at the Landfill Site 98
4.3.6 Validation of the Regression Model Using the Highway 401 Site Data 106
4.3.7 Sensor Performance in Different Air Temperatures at the Highway 401 Site 107
4.3.8 Sensor Performance in Different Speeds at the Highway 401 Site 108

4.3.9 Data Preparation 109
4.3.10 Summary of the Analysis of Data from the Highway 401 Site 110
4.4 Effect of Pavement Temperature on Polymer Piezoelectric Sensors under Highway 401 Site Typical Traffic Stream 111
4.4.1 Effect of Pavement Temperature on All Weight Classes 111
Chapter 5 Summary and Conclusions 113
5.1 Research Summary 113
5.2 Conclusion 114
5.3 Contributions 115
5.4 Limitations 115
5.5 Future Work 116
Bibliography 117
Appendix A Roughness and IRI Measurements and WIM Installation Details at the Landfill Site 123
Appendix B 132
Performance Comparisons by the Factorial Experiment Method 132
Appendix C The Matching Algorithm between the WIM Station and the Main Scale House and Statistical Analysis for Heavy Truck at the Landfill Site 141
C.3.1 Introduction 164
C.3.2 Waste Management (WM) Garbage Trucks 164
C.3.3 Results 167
Appendix D 170
Manual Calibration Sheets 170

List of Figures

Figure 1-1-History of CPATT WIM installations 3
Figure 1-2- The thesis methodology 7
Figure 1-3- The CPATT test site at the Erb Street Landfill 8
Figure 1-4- Stations 12+230 and 12+350 (Google Maps Canada 2011a) 9
Figure 2-1- Typical configuration of Bending Plate or Load Cell 13
Figure 2-2- An example of piezoelectric sensor configuration 15
Figure 2-3- Dynamic tire load over piezoelectric sensors 15
Figure 2-4- WIM System Operation Procedure 16
Figure 2-5- Pavement layers at the CPATT sites, (a) Landfill, (b) Highway 401, section 12+230 27
Figure 2-6- (a) Ceramic piezoelectric sensor, (b) Sensor structure 28
Figure 2-7- The Ceramic sensor model based on location of axle’s gravity center 29
Figure 2-8– Pavement structure at the test site in Denmark 31
Figure 3-1- The Landfill site at the Region of Waterloo 42
Figure 3-2- The Landfill site including hot-laid 3 (HL3), polymer-modified asphalt (PMA), stone mastic asphalt (SMA) and superpave sections 43
Figure 3-3- The Highway 401 site 43
Figure 3-4- Typical installation configuration and details for ECM® Hestia® WIM system 46
Figure 3-5- The layout of WIM sensor systems at the Landfill site 47
Figure 3-6- CPATT Instrumentation including WIM sensor systems at the HWY 401, sections 12+230 and 12+350 48
Figure 3-7- CPATT Instrumentation including WIM sensor systems at the HWY 401 site, section 12+230 49
Figure 3-8- The layout of WIM sensors systems at the Highway 401 site, section 12+230 (the polymer piezoelectric set is at the right side) 50
Figure 3-9– Lineas® sensor 51
Figure 3-10- (a) Quartz sensing elements in a 1 m sensor (b) Cross-section and installation details 51
Figure 3-11- (a) MSI® installation details 52
Figure 3-12- Ceramic piezoelectric sensor installation details (drawn by author based onElectronique Contrôle Mesure 52
Figure 3-13- (a) Auto-calibration (b) Manual calibration process, for the CPATT test site 54
Figure 3-14- The Gantt chart for WIM activities at the Landfill site 55
Figure 3-15- The Gantt chart for WIM activities at the Highway 401 site 56
Figure 3-16- A sample of garbage truck at the Landfill site 56
Figure 3-17- A sample of the Class 9 FHWA 5-axle truck 57
Figure 3-18- The CPATT van 57
Figure 3-19- The location of sensors and path runs on the Lanfill site 58
Figure 3-20- GVW of the van calculated by sensors during 28 May 2008 60
Figure 3-21- Axle spacing of the van calculated by WIM sensors during 28 May 2008 . 60
Figure 3-22- Improvements in the estimations of polymer and ceramic piezoelectric sensors 61

Figure 3-23- The Manual Calibration Sheet designed for the WIM sites........................ 62
Figure 3-24- Layout of the quartz and polymer sensors at the Highway 401site 65
Figure 3-25- The installed Thermistor string covered by 12 cm asphalt.......................... 65
Figure 3-26- The quartz piezoelectric sensors' signal for a three-axle garbage truck...... 67
Figure 3-27- Polymer piezoelectric sensors signal for the CPATT van at 30 km/hr........ 67
Figure 3-28- Polymer piezoelectric sensors signal for the CPATT van at 55 km/hr........ 67
Figure 3-29- Polymer sensors (installed by IRD) signal for a three-axle garbage truck .. 68
Figure 3-30- Polymer (IRD) and Quartz (Kistler) sensors' signal for a two-axle vehicle 68
Figure 4-1- Design of the factorial experiment... 71
Figure 4-2-Calibration and supply of data schedules at the Landfill and Highway 401 sites 72
Figure 4-3– The effect of air temperature on piezoelectric WIM sensors 74
Figure 4-4– The interaction effect for speed by air temperature in the temperature experiment (quartz).. 75
Figure 4-5– Plot of the quartz residuals for the temperature and speed experiment 75
Figure 4-6– The interaction effect for air temperature by speed in the temperature experiment (polymer).. 76
Figure 4-7– The interaction effect for speed by air temperature in the temperature experiment (polymer).. 76
Figure 4-8– Plot of the polymer residuals for the temperature and speed experiment..... 77
Figure 4-9– The interaction effect for air temperature by speed in the temperature experiment (ceramic) 78
Figure 4-10– Plot of the ceramic residuals for the temperature and speed experiment.... 78
Figure 4-11– The interaction effect for path run by air temperature (quartz).................. 79
Figure 4-12– The interaction effect for path run by air temperature (polymer) 80
Figure 4-13– The interaction effect for air temperature by path run (polymer) 80
Figure 4-14– The interaction effect for path run by air temperature (ceramic)................ 81
Figure 4-15– The interaction effect for air temperature by path run (ceramic)................ 81
Figure 4-16– The interaction effect for speed by air temperature (quartz)....................... 82
Figure 4-17– The interaction effect for speed by air temperature (polymer) 83
Figure 4-18– The interaction effect for speed by air temperature (ceramic).................... 83
Figure 4-19– The interaction effect for air temperature by speed (ceramic).................... 84
Figure 4-20– The interaction for speed by air temperature for the recalibrated quartz sensors.. 85
Figure 4-21– The interaction for speed by air temperature for the recalibrated polymer sensors.. 85
Figure 4-22– The interaction for speed by air temperature for the recalibrated ceramic sensors.. 86
Figure 4-23- The FHWA's class 6, garbage truck, the Landfill site................................ 90
Figure 4-24- The FHWA's class 9, 3S2 (3-axle tractor, 2-axle semitrailer) truck, the Highway 401 site 90
Figure 4-25- Vehicle Classification and the frequent truck (class 6), the Landfill site in July 2010.. 91
Figure 4-26- Vehicle Classification and the frequent truck (class 9), the Highway 401 site in November 2010.. 91

Figure 4-27- Gross weight spectrum of class 6 trucks by quartz sensor, the Landfill site in July 2008 ... 92
Figure 4-28- Gross weight spectrum of class 9 trucks by polymer sensor, the Highway 401 site in November 2010 ... 92
Figure 4-29- Polymer sensor estimates at different weight ranges, the Highway 401 site95
Figure 4-30- Polymer sensor estimates at different weight ranges, the Highway 401 site96
Figure 4-31- Steering axle versus GVW for unloaded data in March 2011, the Highway 401 site ... 97
Figure 4-32- Steering axle versus GVW for loaded data in March 2011, the Highway 401 site ... 97
Figure 4-33- Static GVW versus polymer piezoelectric GVW estimation for all matched vehicles, the Landfill site in July 2008 ... 99
Figure 4-34- Static GVW versus quartz piezoelectric GVW estimation for all matched vehicles, the Landfill site in July 2008 ... 99
Figure 4-35- Static GVW versus ceramic piezoelectric GVW estimation for all matched vehicles, the Landfill site in July 2008 ... 100
Figure 4-36- Static GVW versus polymer piezoelectric GVW estimation for matched heavy trucks, the Landfill site in July 2008 ... 100
Figure 4-37- Polymer piezoelectric standardized residuals against predicted value of GVW (adequacy check for the regression model in Figure 4-33) ... 101
Figure 4-38- Lambdas for the polymer sensor estimation and static GVW transformations, the Landfill site ... 103
Figure 4-39- Normal Probability Plot of transformed polymer piezoelectric GVW estimations for the Landfill site, July 2008 ... 104
Figure 4-40- Stabilized variance of error of polymer sensor GVW estimations ... 104
Figure 4-41- The regression model of polymer piezoelectric estimations after transformation, the Landfill site, July 2008 ... 105
Figure 4-42- Static GVW versus polymer piezoelectric estimation for all matched vehicles for the Landfill site, October 2008 ... 106
Figure 4-43- The regression model of polymer piezoelectric estimations after transformation for the Landfill site, October 2008 ... 107
Figure 4-44- Polymer sensor estimates against air temperatures, the Highway 401 site 108
Figure 4-45- Polymer sensor estimates at air temperatures higher than 6^{o}C, the Highway 401 site ... 108
Figure 4-46- Polymer piezoelectric sensor estimates at different speeds for the Highway 401 site ... 109
Figure 4-47- Effect of cold pavement temperatures on polymer piezoelectric sensor's estimation at the Highway 401 site ... 111
Figure 4-48- Effect of cold pavement temperatures on polymer piezoelectric sensor's estimations for unloaded trucks at the Highway 401 site ... 112
Figure 4-49- Effect of cold pavement temperatures on polymer piezoelectric sensor's estimations for loaded trucks at the Highway 401 site ... 112

List of Tables

Table 2-1- WIM system classification and application 11
Table 2-2- WIM requirements for functional performance 11
Table 2-3- Economic analysis of WIM systems 17
Table 2-4- The CPATT Costs of MS-WIM System and Installation Per Lane 18
Table 2-5- Initial Cost for the Least Expensive Piezoelectric Sensor Per Lane 18
Table 2-6- Initial Costs for Quartz, Polymer and Ceramic Piezoelectric Sensors Per Lane 19
Table 2-7- Performance reqirements for WIM systems for 95% compliance 24
Table 2-8- Type I WIM Thresholds for roughness Indices 25
Table 2-9- Type II WIM Thresholds for roughness Indices 25
Table 2-10- Expected gross and steering axle weights 35
Table 3-1- Categorizing the percentages of runs in three fractions of accuracies with the van 61
Table 4-1– Air temperature effects on WIM sensors' GVW estimation at the Landfill site, May 28, 2008 74
Table 4-2– ANOVA table for air temperature and speed effects on the quartz sensors... 74
Table 4-3– ANOVA table for air temperature and speed effects on the polymer sensors 76
Table 4-4– ANOVA table for air temperature and speed effects on the ceramic sensors 77
Table 4-5– ANOVA summary in the temperature experiment including the means of GVW estimations and errors at factor levels 88
Table 4-6– ANOVA summary in the path run experiment including the means of GVW estimations and errors at factor levels 88
Table 4-7– ANOVA summary in the speed experiment including the means of GVW estimations and errors at factor levels 89
Table 4-8- Typical static axle loads and GVW of Class 9 loaded trucks 93
Table 4-9- Axle loads and gross weights of Class 9 unloaded trucks 93
Table 4-10- Typical axle and gross weights of COE trucks 94
Table 4-11- Typical COEs' steering axle and gross weights estimated by polymer piezoelectric, Nov. 2010 94
Table 4-12- Static versus polymer piezoelectric estimation of GVW of traffic stream at the Landfill site 98
Table 4-13- Model Diagnostic for the Landfill Site, July 2008...................................... 105

Chapter 1
Introduction

The first highways in Canada were the rivers and lakes. Native people, explorers, settlers and soldiers sledged the frozen waterways in winter and traveled rivers by canoe in summer. In 1915, Ontario accomplished the construction of a concrete highway from Toronto to Hamilton, which was one of the longest intercity concrete roads in the world and the first one of its kind in that province (Gilchrist 2008). Asphalt concrete in North America as well as other parts of the world has been widely used since the 1920s. The word asphalt is derived from Latin word "asphalton" (Abraham 1938). Ancient Middle Eastern people used natural asphalt deposits as a mortar (for between bricks and stones, ship caulking, and waterproofing). The Persian word for asphalt is "mumiya". Ancient Egyptians also used asphalt to preserve mummies (Pringle 2001). Most roads in Canada are paved with asphalt concrete.

Recent statistics show that in 2005 in the United States, trucks roughly account for 359 billion kilometers of travel, which accounts for 7.5% of total vehicle kilometers of travel on the road in this country. In Canada, the percentage is a little bit higher. In 1998 in Canada, trucks traveled 23 billion kilometers, which was about 8.5% of total vehicle-kilometers of travel (Industry Canada 1998). In 2005, the percentage was 8.8% and was increased to 9.6% in 2008, mainly in Quebec, Manitoba and Ontario. Between 2000 and 2008, the number of trucks grew for 28%, which is 3.1% annually. (NRCan, Office of Energy Efficiency 2010). In addition, roughly 53% of exports to the U.S and 78% of all imports from the U.S were shipped by truck in 2004. In 2005, the trucking industry recorded 3.7% annual growth, which was the second largest increase among the eight segments in the nation's transportation sector (after air transportation, which had 10.8% annual growth) (Statistics Canada 2006). Therefore, transportation by trucks plays a major role in the economy of Canada and the United States. However, the more trucks on the roads, the more possibility of overweight vehicles. This will cause significant damage to the pavements and will reduce the lifespan of roads, which means substantial wastes in the nation's assets.

To overcome the overweight problem, weigh-in-motion (WIM) systems have been used for over 50 years to provide traffic-monitoring, data collection for pavement research and design, and to improve the capacity of static weigh station operations. The application of WIM systems is increasing all over the world; however, there is still a lack of understanding about how dependent the sensors' estimation accuracy are on climate and traffic conditions, proper installation procedures, pavement design for WIM, choice of sensor type for location, and calibration processes, specifically for asphalt concrete pavements which will affect collecting reliable, precise data.

1.1 Motivation

Various problems have been noted with WIM piezoelectric sensors installed on pavement, even when the road is flat and the sensors are installed correctly. These are associated with performance of the sensors and indicate a significant influence of traffic and environment conditions such as pavement or air temperature, weight and speed of vehicle. To estimate the effects of environmental conditions on WIM sensors' performance, the author and CPATT (Center for Pavement and Transportation Technology) colleagues designed and conducted two comprehensive field installations involving three types of piezoelectric WIM sensors. The field installations (or "test sites") are at the Waste Management facility of the Region of Waterloo and on Highway 401 eastbound between exits 238 and 250 located near Woodstock, Ontario.

1.2 Problem Statement

The CPATT has a history of WIM sensor installations (Figure 1-1). In September 2003, a set of piezoelectric polyvinylidene fluoride (PVDF) WIM sensors manufactured by Measurement Specialties, Inc. (MSI) was installed on the two-lane stone mastic asphalt (SMA) section of the test track at the Erb Street Landfill at the Waterloo Waste Management Division. The system mainly consisted of two piezoelectric sensors and two inductive loops on each lane, and a roadside cabinet for the WIM electronics. In the spring of 2006, a detailed field survey found that the sensors on the southbound lane were damaged. In June 2006, the damaged sensors were replaced with the same type of sensors with the same configuration of loop-sensor-sensor-loop. In September 2007, CPATT decided to install a Multiple-Sensor Weigh-In-Motion (MS-WIM) system at the same test site. The new system included quartz piezoelectric (Kistler Lineas®), polymer piezoelectric (MSI®) and ceramic piezoelectric (ECM®) sensors at the site near to the previous set. The site was investigated again according to the American Society for Testing and Materials (ASTM) standards document (ASTM E 2415 2005). The site characteristics satisfied most of the standard requirements.

In 2010, the second MS-WIM system was installed on one out of three new experimental pavement test sections at Highway 401, focused on long-life pavement design. The site is located between exits 238 and 250 on eastbound 401 located near Woodstock. The site had already been instrumented with asphalt strain gauges (ASG), earth pressure cells (EPC), moisture probes (MP) and temperature strings (TS).

ID	Tasks at the CPATT Experimental sites	Start	Finish	Duration	Task Notes
1	**Installation of polymer piezoelectric WIM sensors (IRD):** **- Loop-Sensor-Sensor-Loop** **- Both lanes** **- SMA section of the Landfill site**	**01/09/2003**	**31/03/2006**	**135w**	**Data acquisition from SB and NB until Spring 2006 (damaged sensors reported on the SB lane)**
2	**Hot asphalt mixture patching rehabilitation** **- SMA section at the Landfill site** **- Installation of polymer piezoelectric sensors (IRD)** **Loop-Sensor-Sensor-Loop** **Southbound (SB) lane**	**01/05/2006**	**31/08/2006**	**17w 4d**	**Including the calibration of the WIM system**
3	**Continuous Data Supply**	**01/09/2006**	**31/07/2007**	**47w 3d**	
4	**MS-WIM installation at the Landfill site** **- Procurement of quartz, polymer and ceramic sensors and installation requirements** **- Sensor-Loop-Sensor** **- Southbound (SB) lane** **- SMA section of the Landfill site**	**03/09/2007**	**28/09/2007**	**4w**	**The previously installed IRD sensors on SB lane have been appended to this system**
5	**Start up, as-built, IRI measurements**	**01/10/2007**	**31/12/2007**	**13w 1d**	
6	**Manual and Auto-Calibration, Continuous data supply**	**01/01/2008**	**01/08/2011**	**187w**	
7	**MS-WIM installation at the Highway 401 site** **- Procurement of quartz and polymer sensors and installation requirements** **- Prepared drawings, installation and calibration guideline reports, project management** **- Sensor-Loop-Sensor** **- Eastbound (EB) lane** **- Perpetual pavement design with RBM section**	**02/08/2010**	**30/09/2010**	**8w 4d**	**Funded by CPATT and MTO, installation contracted with Aecon**
8	**As-built, WIM system trouble-shoot**	**04/10/2010**	**29/10/2010**	**4w**	
9	**Manual Calibration, Continuous data supply**	**04/11/2010**	**27/07/2011**	**38w**	

Figure 1-1-History of CPATT WIM installations

The new WIM system at this site includes one set of quartz, and one set of polymer piezoelectric sensors with the loop-sensor-loop configuration. The installed piezoelectric WIM sensors are generally described as below:

1. MSI (Measurement Specialties, Inc.), the MSI Roadtrax® Brass Linguini® axle sensor (polarized polymer WIM sensor)
2. Kistler (Kistler Instrumente AG), Lineas® quartz piezoelectric WIM sensor Type 9195E
3. ECM (Electronique Contrôle Mesure), Piezolor type PE, (polarized ceramic WIM sensor)

The sensitivity to environmental conditions such as temperature, specifically on polymer and ceramic piezoelectric WIM sensors, has been generally known. This sensitivity is modeled in this thesis. Also investigated are the effects of vehicle's weight and speed on the sensor performance. The thesis considers the parameters associated with a sensor's performance, which can affect the measurement results, including conformity (same sensor response in same conditions), uniformity (same wheel path conditions along the sensor), linearity (how linear is the output of the sensor), and sensitivity (how sensitive is the sensor to the environmental conditions). This sheds light on the performance of piezoelectric WIM sensors under different loads and environmental conditions and creates the potential for developing an algorithm for compensating for the effects of climate and traffic major conditions including air or pavement temperature, and weight and speed of vehicle on a polymer piezoelectric sensor's outputs. This would improve the accuracy of the lowest cost WIM alternative

1.3 Background and Review

The ASTM defines a WIM system as:

"A set of sensors and supporting instruments that measure the presence of a moving vehicle and the related dynamic tire forces at specified locations with respect to time; estimate tire loads; calculate speed, axle spacing, wheelbase, vehicle class according to axle arrangement, and other parameters concerning the vehicle; and process, display, store, and transmit this information" (ASTM E 1318 2009). In 1951, Normann and Hopkins of the Bureau of Public Roads implemented one of the first attempts to build up a WIM system (as cited in Lee, Garner 1996). Consequently, in Virginia the first system constructed for aircraft weighing was comprised of a floating reinforced concrete slab supported by four strain-gage load cells. In the early 1960s, WIM systems were installed in the United States, Europe, and Japan. Soon after the large platform-type scales, more portable and smaller WIM systems were developed. Before the end of the 1960s, electronic instrumentation for processing of signals from transducers became available (Lee, Garner 1996).

Since the 1980s, WIM technology has been widely used to improve infrastructure design and enforcement efficiency. WIM of vehicles on the road monitors the axle loads of vehicles. This is necessary for design and maintenance of infrastructure and management of freight traffic.

The acceptable estimation procedure of the less expensive WIM sensors is very dependent on the auto-calibration process. This process is proprietary to the vendors and cannot be accessed by a user to construct a custom-make algorithm, which can work with Ontario’s cold and humid climate in the south. Nor can the performance of such proprietary auto-calibration algorithms be easily characterized. Producing more accurate and reliable WIM data will support efforts to convert the large quantities of WIM data into useful knowledge for: (a) collection of weight data for use in pavement design and management systems, (b) for vehicle classification, and (c) for weight enforcement.

In Summary, demand for more accurate and reliable WIM sensor systems is increasing due to their capability to provide the managers, designers and decision makers of road systems with up to date data and online measurements of axle loads.

1.4 Objectives of the Research

To acquire knowledge about calibration processes, pavement design for WIM, and choice of sensor type for location, specifically for flexible pavements, this research is intended to explore the behaviour of WIM piezoelectric sensors under different loads and environmental conditions. Specifically, the objective is to develop the basis for sensor estimation compensation, specifically for the least expensive polymer piezoelectric WIM sensor, in order to provide:

1. Recommendations for more effective calibration procedures for the WIM systems, and
2. Better performance for lowest cost.

1.5 Scope of the research

The scope of this research study is to investigate environmental effects on piezoelectric weigh-in-motion systems, specifically for polymer piezoelectric WIM sensors installed in the stone-mastic and perpetual pavement section designs at the conditions as follows:

1. Temperatures from -4 ^{o}C to +20 ^{o}C
2. Vehicle speeds from 30 to 110 km/hr
3. Vehicle weights from 1 to 40 tons

1.6 Methodology

Review of the literature was mainly focused on the effects of climate and traffic conditions on sensors' outputs and also on the data processing and quality control. The first round of literature review was carried out in 2007 and 2008, focusing on site selection, sensor basics and performance, installation, calibration and modeling the interaction between axle loads and flexible pavement using the finite difference method.

The second round was focused on sensors' performance under different environmental conditions, statistical methods for modeling, data processing and data quality control in order to find the most effective method for modeling the sensor's responses under typical climate and traffic conditions at both CPATT's experimental sites. This research study requires taking into account in a realistic way the complex interaction between sensor performance and the factors related to traffic and weather characteristics. To deal with this situation, the following tasks were accomplished at both experimental sites:

- Assessment of pavement surface conditions using International Roughness Index (IRI) (at the Landfill site) (APPENDIX A),
- Sequential manual calibration of WIM system to capture seasonal performance of sensors,
- Acquisition of typical traffic data,
- Factorial experiments to find the influences of major factors and the most influential factor (at the Landfill site),
- Statistical analyses of trucks static weights to find characteristic gross and steering axle weights,
- Statistical analyses of axle loads to split the loaded and unloaded data (at the Highway 401 site),
- Matching process (at the Landfill site), and
- Statistical analyses including regression modeling and frequency analyses.

The flowchart of methodology illustrated in Figure 1-2.

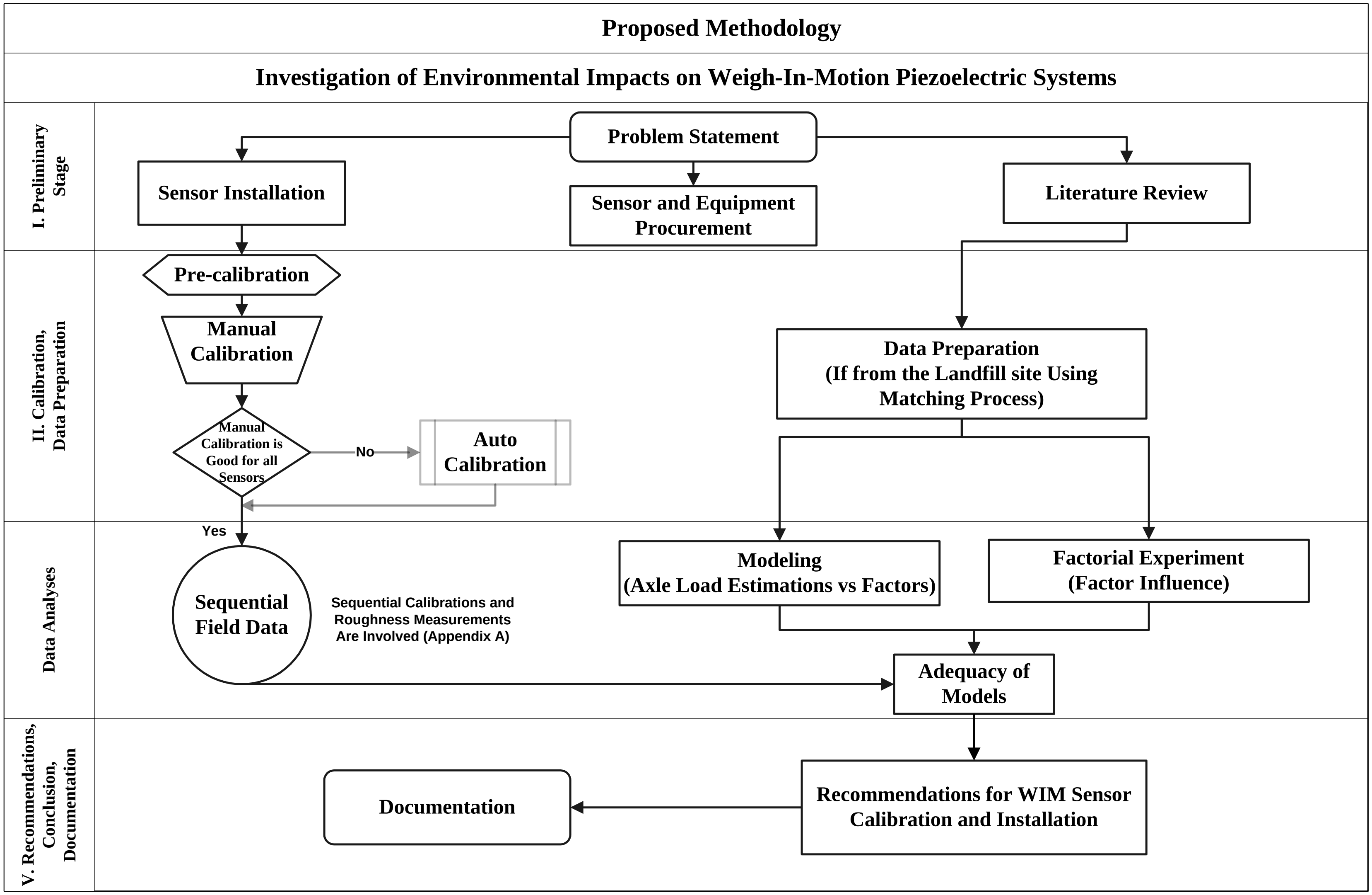


Figure 1-2- The thesis methodology

1.7 CPATT's Pavement Testing Facilities

1.7.1 The Landfill Site

The experimental site of CPATT in Waterloo is located at the Waste Management Division at the Regional Municipality of Waterloo which is located at 925 Erb Street West. The test track is close to the University of Waterloo and has a static weigh station upstream. Therefore, accurate vehicle weights are readily available, for those vehicles whose paths subsequently pass the WIM site (Figure 1-3).

Figure 1-3– The CPATT test site at the Erb Street Landfill (Google Maps Canada 2011b)

1.7.2 The Highway 401 Site

The experimental site of CPATT at Highway 401 is located between exits 238 and 250 and between Waterloo and Woodstock in Ontario at station 12+230 (Figure 1-4), which has a perpetual pavement design with a rich bottom mix layer (RBM).

1.8 Organization of the Thesis

This thesis consists of five chapters organized by topic. Chapter 1 provides an overview of the research problem, objectives and a brief description of weigh-in-motion sensors and installations. At the end of the chapter 1, the expected objectives of the research are summarized. Chapter 2 provides some background knowledge about WIM sensors and systems, factors affecting the accuracy of WIM sensors and reviews the research studies carried out in WIM in

North America and Europe, which are two major users of WIM systems. At the end of chapter two, the summaries of studies on effects of climate factors on WIM sensors and proprietary auto-calibration algorithms on polymer and ceramic piezoelectric systems are discussed. Chapter 3 discusses the methodology of this research including modeling of factor effects by the factorial experiment method and methods of analysis of the data. Chapter 4 presents analysis of the data. Chapter 5 summarizes the research and discusses possibilities for future developments.

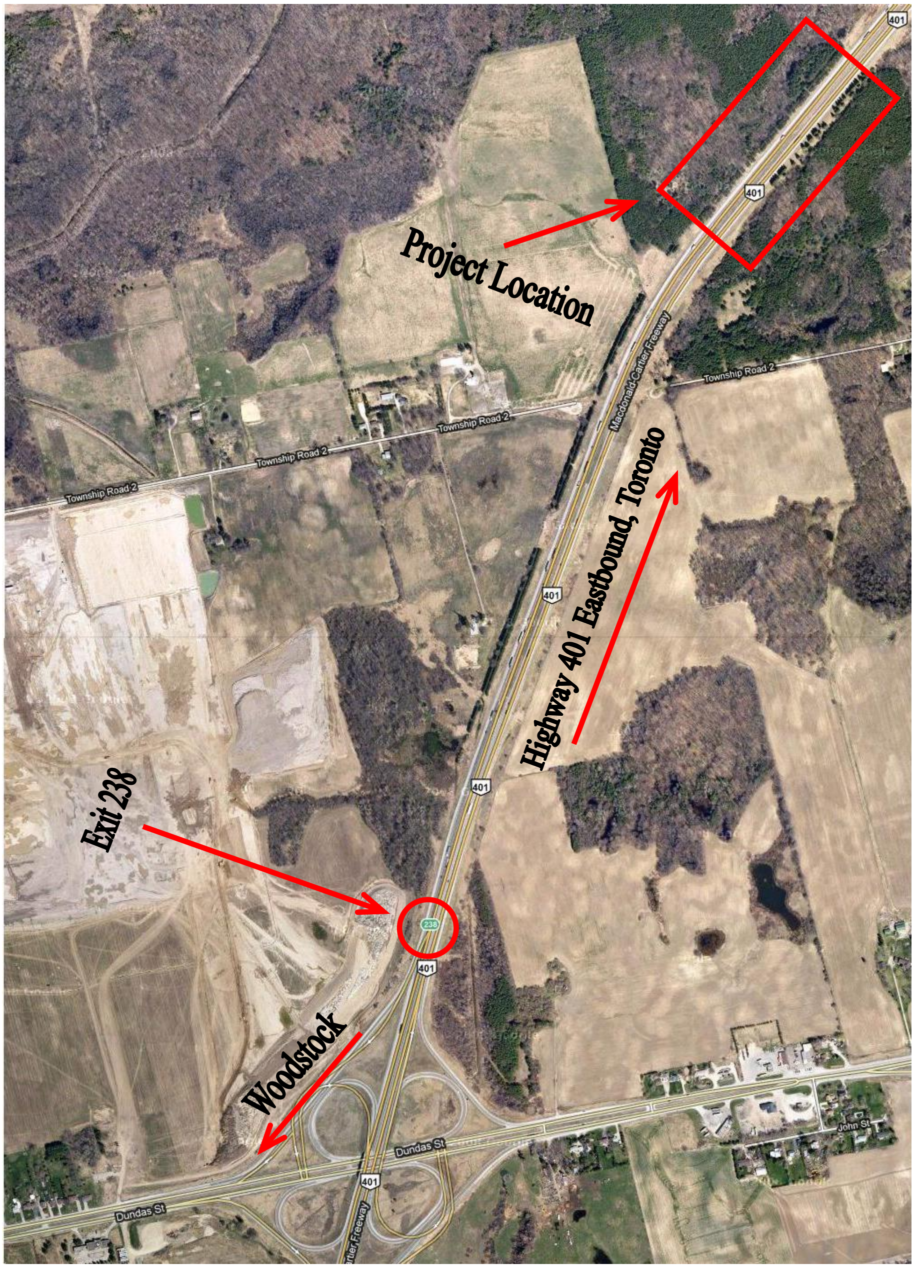


Figure 1-4- Stations 12+230 and 12+350 (Google Maps Canada 2011a)

Chapter 2
Literature Review

2.1 Introduction

Several functional and structural goals are involved in the provision of cost effective, long lasting and reliable installation and performance of WIM sensors during all weather conditions. Researchers are continually trying to better understand the behaviour of WIM sensors under traffic loadings and environmental cycling to be able to invent methods for improving the design, construction, installation and maintenance in order to extend service life and/or reduce user costs. An introduction to the basic concepts of weigh in motion along with some related prior studies are addressed in this chapter. These studies on modeling of sensors, pavement, and sensor-pavement systems provided the research presented in this thesis with approaches for the details of modeling and verification of results.

2.2 Weigh-In-Motion Sensor

According to the ASTM, Weigh-In-Motion is defined as "The process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle" (ASTM E 1318 2009). The gross weight of a vehicle is divided into loads, which are carried by the tires of each axle or axle group of the vehicle. When a vehicle travels over a sensor, the sensor receives a portion of the full load and transduces that into a voltage as an output, which is then transformed into the gross weight of the vehicle using algorithms and software. A WIM system has the ability to continuously measure axles and vehicle weights, count the number of axles and vehicles, classify them according to weight category, and record their speeds, without any interruption. The applications for WIM technology can be generalized in three main groups as follows:

1. Pavement design and infrastructure management,
2. Freight/trade planning and regulation, and
3. Detection and enforcement.

ASTM E 1318-09 classifies WIM systems into four types regarding their application. The description of each type, intended accuracy and user requirements are mentioned in the standard. WIM system types are different in their speed ranges, data recording capabilities and the application they are designed to meet in terms of the needs of users. Table 2-1 shows the classification and application information, and Table 2-2 demonstrates the requirements of functional performance of WIM systems.

Table 2-1- WIM system classification and application (McCall, Vodrazka 1997 with minor corrections according to ASTM E 1318-09)

	Classification			
	Type I	Type II	Type III	Type IV
Speed Range	**16-130 km/hr (10-80 mph)**	**24-130 km/hr (15-80 mph)**	**16-130 km/hr (10-80 mph)**	**3-16 km/hr (2-10 mph)**
Application	**Traffic data Collection**	**Traffic data Collection**	**Weight Enforcement**	**Weight Enforcement**
Number of Lanes	Up to four	Up to four	Up to two	Up to two
Bending Plate	✓	✓	✓	✓
Piezoelectric Sensor	✓	✓		
Load cell	✓	✓	✓	✓
Wheel Load	✓		✓	✓
Axle Load	✓	✓	✓	✓
Axle-Group Load	✓	✓	✓	✓
Gross Vehicle Weight	✓	✓	✓	✓
Speed	✓	✓	✓	✓
Axle Spacing	✓	✓	✓	✓
Vehicle Class	✓	✓		
Site Identification Code	✓	✓	✓	✓
Lane and Direction of Travel	✓	✓	✓	
Date and Time of Passage	✓	✓	✓	✓
Sequential Vehicle Record #	✓	✓	✓	✓
Wheelbase (front to rear axle)	✓	✓		
Equivalent Single-Axle Load	✓	✓		
Violation Code	✓	✓	✓	✓

Table 2-2- WIM requirements for functional performance (ASTM E 1318 2009)

Function	Tolerance for 95% Probability of Conformity				
	Type I	Type II	Type III	Type IV	
				Value ≥ kg (lb)	±kg (lb)
Wheel Load	± 25%	N/A	± 20%	2300 (5000)	100 (300)
Axle Load	± 20%	± 30%	± 15%	5400 (12000)	200 (500)
Axle group Load	± 15%	± 20%	± 10%	11300 (25000)	500 (1200)
Gross Vehicle Weight	± 10%	± 15%	± 6%	27200 (60000)	1100 (25000)
Speed	± 2 km/h (1 mph)				
Axle Spacing	± 0.15 m (0.5 ft)				

2.3 Types of Weigh-In-Motion Systems

2.3.1 Bending Plate WIM System

A typical bending plate is a WIM system, which employs strain gauges as sensing elements. Therefore, when a vehicle travels over the bending plate system, the strain gage measures the strain and knowing the mechanical properties of the plate, consequently calculates the dynamic load.

A bending plate WIM system includes one or two scales. The scales are placed in the lane perpendicular to traffic direction. These WIM systems can be either permanent or portable and include one scale and two inductive loops in a minimum configuration. The inductive loops are placed before and after the scale. Figure 2-1 illustrates that to measure the speed of vehicle; an axle sensor can be placed after the scale and before the second loop, downstream. The upstream loop, triggers the system and the downstream loop is used for speed and axle spacing calculations. Based on user’s requirements and the number of scales placed in the lane, the bending plate WIM system is classified according to ASTM as type I, II, III or IV (McCall, Vodrazka 1997).

2.3.2 Load Cell WIM System

A load cell WIM system similar to other WIM sensors is placed in the travel lane perpendicular to the direction of travel and comprises a single load cell with two scales, which work independent of each other. The scales detect wheels of an axle, record the weights and calculate the axle weight by summing the measured weights.

Off-scale detectors are placed in the configuration and integrated into the scale system to detect loads, which are out of the weighing surface. A common load cell system is comprised of a load cell, an inductive loop and an axle sensor. The upstream inductive loop triggers the system. To facilitate measuring axle spacing and vehicle speed, the designers may place the second loop detector downstream of the system. In such a system, the configuration is similar to a bending plate (Figure 2-1). Depending on the design of the site, the load cell WIM system is classified according to ASTM as type I, II, III or IV (McCall, Vodrazka 1997).

2.3.3 Piezoelectric WIM System

2.3.3.1 Introduction to Piezoelectricity

Piezoelectricity relies on the piezoelectric effect, which was discovered by Pierre and Jacques Curie in the late 19th century (Wharton 2006). They observed the transformation of a mechanical energy as an input into an electrical output as surface charges appearing on some naturally occurring and specially prepared crystals such as quartz, tourmaline and topaz.

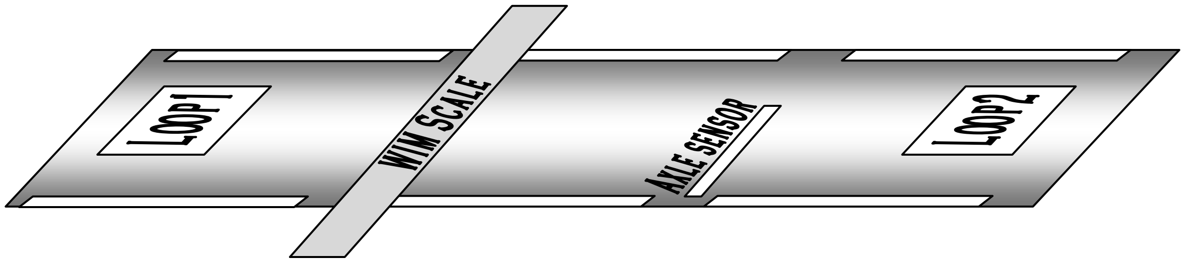


Figure 2-1- Typical configuration of Bending Plate or Load Cell (McCall, Vodrazka 1997)

Piezo is the Greek word for pressure. A piezoelectric material produces electrical charges when the material is subjected to a pressure. Those charges are proportional to the applied pressure. These materials would also exhibit the converse piezoelectric effect. Thus, they can be used to convert the electric field to a stress. During a twenty-five year period from1940 to 1965, the piezoelectric properties of certain ceramic materials were also discovered. And in 1969, Kawai found a high piezoelectric property in a polarized polymer called polyvinylidene fluoride (PVDF) (as cited in Piezo Film Sensors 1999). Hence, the 1960s was the first decade for production and application of synthetic polarizable ferroelectric materials.

2.3.3.2 Application of Piezoelectric Materials as WIM Sensors

Two categories of piezoelectric material are predominantly used in WIM sensors. They are synthetic crystal cuts and polarizable ferroelectric ceramic and polymer composites. A polarized piezoelectric sensor for instance, uses a ceramic tape or cable embedded within a long block of elastometric material, while a synthetic crystal piezoelectric sensor uses quartz, tourmaline, topaz, etc. as a sensing element in its structure (Wharton 2006). Both sensor blocks will be installed in a narrow slot on the pavement. Each kind of piezoelectric WIM sensors has its own advantages and disadvantages. The sensors using quartz can benefit from the following advantages:

- Quartz is widely known for its ability to perform accurate measurement tasks. This crystal is used extensively in everyday applications for time and frequency measurements such as in wristwatches and radios to computers and home appliances.
- Quartz crystal is naturally piezoelectric, and thus has no tendency to relax to an alternative state. It has the most stable state among all piezoelectric materials. This important feature provides quartz WIM sensors with long-term stability and repeatability.
- Quartz does not have any output due to temperature change (pyro-electricity effect), which provides stability in thermally active environments.

- The voltage sensitivity of quartz is relatively high compared to most ceramic materials because of its low capacitance value. This property makes it ideal for use in voltage-amplified systems.

On the other hand, the polarized polymer and ceramic sensors have the following benefits:

- The sensor costs are lower than quartz WIM sensors, and
- The installation is easier and cheaper.

However, polymer and ceramic piezoelectric sensors have the following disadvantages:

- The sensor is more prone to physical damage under heavy loads or extrinsic degradation due to environmental effects than quartz sensors, leading to sensor failure.
- The sensor is sensitive to temperature fluctuations (pyroelectricity effect). For instance, PVDF material (polymer piezoelectric sensors) expands in thermally active environments, which results in decreasing the average polarization of the piezoelectric film and consequently generating a charge on the surface of the film. Therefore, the amount of this additional electrical charge is proportional to the rate of temperature change which is described by the pyroelectric charge coefficient (ρ) (Piezo Film Sensors 1999) (Ce-Wen 1994) (Piezo Film Sensors 1999) (Piezo Film Sensors 1999) (Piezo Film Sensors 1999).
- The sensor is subject to intrinsic degradation since its polarity can change with time.
- This type of sensor requires more calibration efforts, partly because polarized piezoelectric materials have less stability and repeatability.

2.3.3.3 Piezoelectric Sensor

A piezoelectric WIM system utilizes piezo sensors, with which the system can detect a pressure applied on it and estimate the static weight of a moving wheel or axle. Piezo sensing elements either can be polarized such as polymer and ceramic piezoelectric material or synthetic crystals such as quartz sensing element. Depend on the application of the device and the number of sensors on the lane, the piezoelectric WIM system is classified according to ASTM as Type I to IV (McCall, Vodrazka 1997).

A typical example of a piezoelectric WIM system represents two piezo-sensors and two loop detectors placed upstream and downstream from the sensor. The upstream loop detects the approaching vehicle and alerts the system to sample at a high frequency. The downstream loop is used in conjunction with upstream loop to measure axle spacing and vehicle speed. Figure 2-2 demonstrates an example configuration of a piezoelectric WIM system. The response is a voltage, which changes in proportion to the pressure applied (Figure 2-3). Once a vehicle passes over a piezoelectric sensor, the sensing elements are induced to create charges. The system records these charges and calculates the dynamic load using the calibration parameters. The static load is estimated then from the calculated dynamic load.

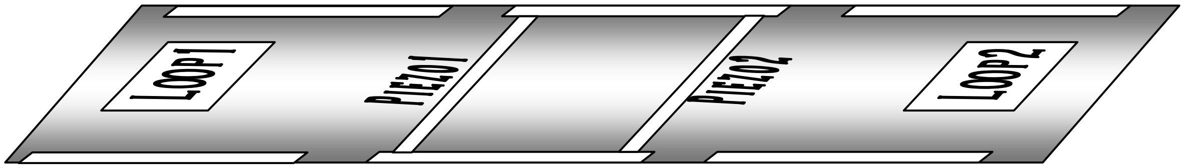


Figure 2-2- An example of piezoelectric sensor configuration

The mathematical relationship that governs the output of piezoelectric WIM sensors can be described as follows:

$$\boldsymbol{P = f(V)}$$

Where P is the applied pressure and V is the piezoelectric sensor's output voltage. The applied pressure over the sensor by a tire has an area with a rectangle shape. The wheel weight (W) is a function of the tire print area (A) and the applied pressure (P) as follows:

$$\boldsymbol{W = f(A, P)}$$

The area (A) of the tire print is a function of width (w) and length (l) as follows:

$$\boldsymbol{A = f(w, l)}$$

Width (w) and length (l) of the tire print can also be described as function of length (l) of tire print and function of the duration of time (t) the applied pressure is sensed and speed (v) of vehicle respectively as $\boldsymbol{w = f(l) \quad and \quad l = f(t, v)}$

Therefore, the wheel weight (W) can be formulized as a function of output voltage (V), time (t) and speed (v) of vehicle as follows:

$$\boldsymbol{W = f(t, v, V)}$$

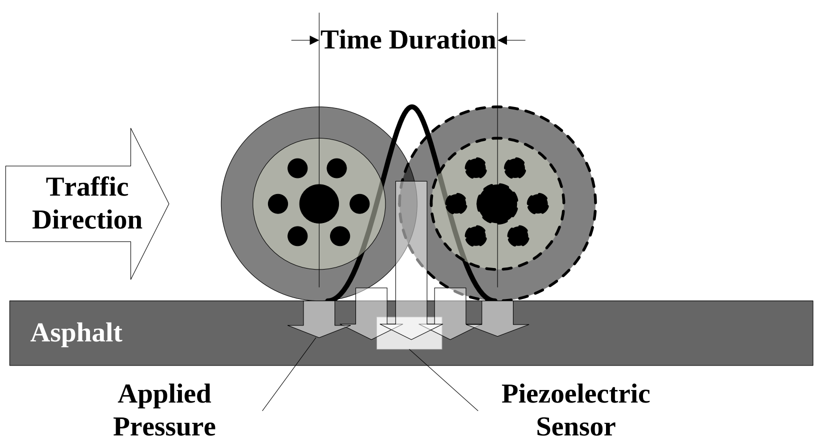


Figure 2-3- Dynamic tire load over piezoelectric sensors

At the CPATT experimental site, The WIM system software settings only accepts sensor-loop-sensor configuration for the type II sensors. This installation configuration is described in Chapter 3.

The WIM systems including sensors and loops produce different outputs when a vehicle passes over the site as illustrated in Figure 2-4. The main outputs are axle spacing, axle load, axle number, time of passing and presence. Other data such as wheelbase, length, class and gross weight are produced using the main outputs. For instance, gross weight is a summation of axle loads and class of a vehicle is produced using a built-in classification algorithm, which uses information such as axle spacing and axle number.

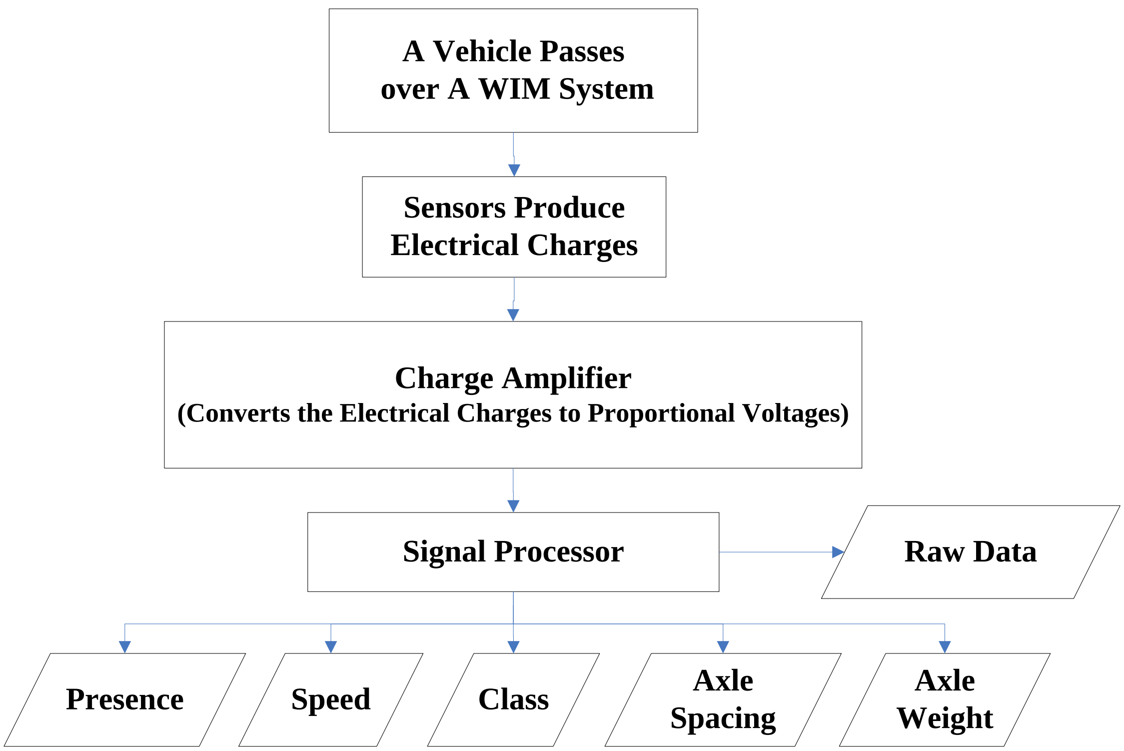


Figure 2-4- WIM System Operation Procedure

2.4 Cost Comparisons

Economic analysis shows there are significant differences between system and maintenance costs of WIM systems, as displayed in Table 2-3 (Taylor and Bergan as cited in McCall, Vodrazka 1997). WIM systems provide different levels of accuracy, installation complexity, initial (sensor, equipment and installation costs per lane) and lifespan costs (estimated based on a 12-year life span per lane including maintenance in three areas of WIM system, the roadway pavement and scale frames, and power and communication). It can be concluded that according to the Table 2-3 (which is perhaps out of date), the piezoelectric sensor system has the lowest cost with an acceptable range of accuracy. This WIM system has also the easiest procedure of installation.

However, in the CPATT experience, the initial cost for installations of MS-WIM systems at the Landfill and Highway 401 sites were approximately US$61,000 (three WIM sensor sets) and US$56,000 (two WIM sensor sets) per lane, respectively (Table 2-4). Therefore, the MS-WIM system initial costs per lane for 12 years life spans for the Landfill and Highway 401 sites will be US$5,100 and US$4,700 respectively (excluding maintenance costs).

Table 2-5 shows that initial costs per lane for installation of polymer piezoelectric sensor for the Landfill and Highway 401 sites were US$26,000 and US$25,000 respectively. The difference in costs is because of sharing some costs such as cabinet and solar panel with other projects in the Highway 401 site. Considering the initial costs at the landfill site, an average cost per lane for 12 years life spans can be estimated approximately US$2,200 for the polymer piezoelectric WIM system (excluding maintenance costs).

Table 2-3- Economic analysis of WIM systems (McCall, Vodrazka 1997)

No.	**WIM System**	**Performance(1)**	**Estimated Initial Cost/Lane(2)**	**Estimated Average Cost Per Lane(3)**
1	Piezoelectric Sensor	± 10%	$9,500	$4,224
2	Bending Plate Scale	± 5%	$18,900	$4,990
3	Double Bending Plate Scale	± (3-5)%	$35,700	$7,709
4	Deep Pit Load Cell	± 3%	$52,500	$7,296

(1)- Percentage of error on GVW at highway speeds

(2)- The initial cost per lane includes the equipment and installation of the WIM system

(3)- Lifespan is considered a 12-year period including structural, communication and WIM system maintenance

Table 2-4- The CPATT Costs of MS-WIM System and Installation Per Lane

Item	Landfill Site (Southbound)		Highway 401 Site (Eastbound)	
	Unit	US$	Unit	US$
4-lane System	1	14000	1	14000
Cabinet	1	3000	1	1000
Solar Panel , Batteries	1	1000	1	1000
Supervision & Training	1	8000	1	8000
Operator & Maintenance System Manuals	1	-	1	-
WIM System Software	1	-	1	-
Quartz piezoelectric Sensors	8	19,000	8	19,000
Quartz piezoelectric Installation Resin	2	500	2	500
Charge Amplifier, Wiring Harness, etc.	1	2,000	1	2,000
Polymer piezoelectric Sensors	2	2,200	2	2,200
Polymer piezoelectric Installation Resin	2	500	2	500
Ceramic piezoelectric Sensors	2	2,500	-	-
Ceramic piezoelectric Installation Resin	2	500	-	-
Shipping	1	2800	1	2800
Tools/Material/Rentals for Installation	-	5000	-	5000
Total Cost	61,000		56,000	

Table 2-5- Initial Cost for the Least Expensive Piezoelectric Sensor Per Lane

Item	Landfill Site (Southbound)		Highway 401 Site (Eastbound)	
	Unit	US$	Unit	US$
4-lane System	1	14000	1	14000
Cabinet	1	2000	1	1000
Solar Panel , Batteries	1	1000	1	1000
Supervision & Training	1	2000	1	2000
Operator & Maintenance System Manuals	1	-	1	-
WIM System Software	1	-	1	-
Polymer piezoelectric Sensor	2	2,200	2	2,200
Other (e.g. Charge Amplifier, Wire, etc.)	1	2000	1	2000
Polymer piezoelectric Installation Resin	2	500	2	500
Shipping	1	800	1	800
Tools/Material/Rentals for Installation	-	1500	-	1500
Total Cost	26,000		25,000	

The initial costs per lane are displayed in Table 2-6 for different WIM systems. The average initial costs per lane for 12 years life spans for the CPATT's WIM sites can be estimated

US$3,800, US$2,300 and US$2,200 for Quartz, ceramic and polymer piezoelectric WIM systems.

Table 2-6- Initial Costs for Quartz, Polymer and Ceramic Piezoelectric Sensors Per Lane

Item	Piezoelectric WIM System					
	Polymer		Ceramic		Quartz	
	Unit	US$	Unit	US$	Unit	US$
4-lane System	1	14000	1	14000	1	14000
Cabinet	1	2000	1	2000	1	2000
Solar Panel , Batteries	1	1000	1	1000	1	1000
Supervision & Training	1	2000	1	2000	1	4000
Operator & Maintenance System Manuals	1	-	1	-	1	-
WIM System Software	1	-	1	-	1	-
Sensor	2	2,200	2	2,500	8	19,000
Other (e.g. Charge Amplifier, Wire, etc.)	1	2000	1	2000	1	2000
Installation Resin	2	500	2	500	2	500
Shipping	1	800	1	1500	1	1500
Tools/Material/Rentals (Installation)	-	1500	-	1500	-	1500
Total Cost	26,000		27,000		45,500	

2.5 Factors Affecting WIM Sensors Accuracy

The general effects of environment on a weigh in motion sensor system are known but not well characterized. In laboratory experiments, many sensors demonstrate acceptable results; however, the installed sensors rarely show the same accuracy. Hence, the installation environment highly affects the sensor performance and accuracy. For instance, ceramic piezoelectric sensors have different performances in different parts of the world such as U.S., Canada, Germany, Australia, Qatar, New Zealand, etc. since these locations have very different climates and different temperatures and moistures can affect the sensors to respond differently (Koniditsiotis 2000).

A Weigh-In-Motion system in comparison with a static weigh scale have higher likelihood of faulting, because a permanent installed WIM system cannot be replaced or repaired and is more prone to estimate weights differently in different climate and traffic conditions. Hence, the long term stability and functionality of members of the system, including sensor rows, pavement in front and behind of sensors loops and wires must be considered significantly more in the design stage than a static weigh station to reach to an acceptable level of system reliability (Scheuter 1998). Any type of weigh sensor or scale will only be able to respond the share of load it gets. The static weight of a vehicle is defined as the weight under perfect conditions such as a perfect level site, a proper suspension for the vehicle, frictionless position and no braking. The error of a WIM sensor in weighing a vehicle is the difference between sensor's estimation and the actual static weight of the vehicle divided by the actual static weight of the same vehicle.

The followings are the possible errors, which might occur, in comparison to static wheel load scales. Comparing these two methods, researchers will be able to understand the performance and behaviour of WIM systems as a well-known and accepted technology. The sources of errors are classified below.

1. **Inaccuracy of the sensor itself due to internal factors -**The difference between what sensors indicate in response to applied load and the applied load (the share of the total load the sensor experiences) is defined as the intrinsic error of the instrument (Scheuter 1998). The errors may occur because of temperature or electromagnetic sensitivity, improper installation, edge effect, eccentric loading, etc.
2. **Inaccuracies due to external factors -** The difference between the static weight of a vehicle and the applied load on a sensor (the share of the total load the sensor experiences) causes play the other major source of error. The installation environment will bring different factors into called external factors, which will affect the sensor‘s output. Some of the factors described below.
   - **Tilting of vehicle -** This factor will change the share of load the system senses from each axle. In addition, the wrong sensor levelling because of improper installation will also cause errors.
   - **Vehicle vibration** - This is the most probable source of error for WIM systems. It depends upon the road conditions and vehicle suspension quality.Therefore, measuring the IRI of the pavement before any installation of WIM sensors for selecting the best site and continuing maintenance of the site and installed sensors are necessary. More information and references on site selection criteria are given in Middleton et al. (2004). In an ideal situation, a vehicle passing over a WIM sensor has no effect from vibration.
   - **Tread of tire** - Tire tread may also affect the sensor system, specifically the ones that have cross grooves like winter tires. The dimension of the groove, the location where the groove crosses the sensor and the sensor width are the parameters that control this error (Scheuter 1998).
   - **Driver's influence on accuracy -** Factors such as changing the vehicle speed may affect the WIM accuracy, especially when higher speeds increase the influences of road imperfections on the sensor responses. Moreover, bypassing the sensor partially may affect significantly the output of the sensor especially in ceramic piezoelectric sensors. This is the reason that in calibration of WIM sensors the driver plays an important role.

2.6 Review of Research in Weigh-In-Motion

2.6.1 WIM Research in North America

The Long-Term Pavement Performance (LTPP) program, started in 1987, aimed to help states and provinces construct and maintain a better performing and cost-effective highway system (LTPP Program). In North America, the LTPP program monitors more than 2,400 flexible and rigid pavement test sections (the United States and Canada). The program is initiated as part of the Strategic Highway Research Program (SHRP). It is currently managed by the Federal Highway Administration (FHWA).

Gillmann (2005), provided an update on the weigh in motion activities in the United States and Canada. The survey indicated that the LTPP program in its final phase is ensuring the availability of a minimum of five-year traffic load data for LTPP experiments. Since November 2004, the second phase of the study to improve the quantity and quality of traffic data aimed to procure, install and maintain WIM systems to make certain of collecting high-quality data.

In addition, the U.S. National Cooperative Highway Research Program (NCHRP) provided the pavement designers with a Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. To estimate the effects of traffic on a pavement, this guide uses axle load spectra instead of Equivalent Single Axle Loads (ESALs), which means that the pressure toward using WIM data for pavement design is increasing. In fact, in Ontario, in 2011, the decision to collect load spectra using WIM for the next generation of pavement design procedures was made. The research also stated that using WIM data in vehicle weight enforcement is also growing. The North American Preclearance and Safety System (NORPASS), and another system called PrePass®, collaborate to electronically identify the vehicles by off-road readers and at the same spot possible violators using the data resulting from their travel over WIM sensors. This system is able to signal the drivers either to bypass or to pull into the static weigh station for verifying the weigh measurement, which can save time and money. For instance, the NORPASS claims that it provides roughly 3 million bypasses per year and based on a study in 2007, by each truck's bypass a saving of approximately US$8.68 will be made, which will be equal to roughly US$26 million for the trucking industry annually (NORPASS).

Additionally, Madanat et al. (2006) described that in the U.S. (California, Kentucky, Indiana, Florida and Minnesota) and in Canada (Saskatchewan), research and development on virtual weigh stations (VWS) are in progress. These stations can integrate data from camera; weigh station, mobile inspection unit and WIM detectors to control the vehicle weights on highways. Bold et al. (Bold et al. October 2006) defines a Virtual Weigh in Motion (VWIM) system and its components as a "nonintrusive, unmanned, automated data collection" system, which is composed of a wireless communications device, remote cameras, electronic transponders, Optical Character Recognition Cameras (OCR) and License Plate Readers (LPR).

2.6.2 WIM Research in Europe

Major developments occurred in weigh in motion technology and its application in Europe after the year 2000. In the 1980s and even in the 1990s, the WIM sensors had durability and accuracy problems. Since 1992, an action under the COST Transport actions (COST 323 Management Committee June 1997) solved some of the problems occurring in the community of WIM users, such as the method of assessing the accuracies and WIM requirements, etc., and the durability of WIM sensors seemed to be improving (Jacob, O'Brien 2005). Additionally, the Weigh-in-motion of Axles and Vehicles for Europe or WAVE project started in September 1996 and ended in June 1999. It was intended to complement the COST 323 project. This project resulted in several improvements, such as experiments with WIM systems in cold climates as an independent test, development of fiber optic WIM sensors, processing of the MS-WIM system output using new algorithms, etc. (European Commission DG VII-Transport 2001).

In the period from 2000 to 2002, the project called "TOP Trial" worked on WIM system design and architecture to achieve the goal of constructing a fully automatic system for overload enforcement, which employed WIM sensors in its structure. This project also had some achievements such as constructing and operating a semi-automatic weight enforcement system, investigating WIM sensor reliability and accuracy, optimizing the sensor layout for achieving the A(5) accuracy class (±5%) according to COST 323 specifications in a Multiple-Sensor WIM site (MS-WIM), using simulation techniques, etc. For instance, Gajda et al. (2007) attempted to model a series of ceramic piezoelectric sensors and aimed at reaching 2-4% accuracy considering road roughness, quantity and type of sensors and distance between them and an algorithm for static load estimation. The results showed that without serious limiting of the vehicles velocity achieving 2-4% accuracy is possible using MS-WIM system including at least 16 ceramic piezoelectric sensors.

This can raise a debate about superiority of two alternative design paradigms: (1) a WIM system including one or two sensor sets of high cost and quality, or (2) an MS-WIM system comprised of more sensors of cheaper and lower quality. Jacob et al. (2005) concluded that since vertical acceleration of vehicles and road imperfections can increase each other during the lifetime of a WIM system the second assumption is definitely the best approach for achieving acceptable accuracies with the average roughness of most pavements. Fully automatic systems for weight enforcement are also being pursued by some projects e.g. Requirements for EnforceMent of Overload Vehicles in Europe (REMOVE) (Van Loo, Henny 2005)

There were also some interests in modeling the sensors by combining the in-situ and lab experiments with finite element analysis to explore the sensor behaviour under different contact load conditions. In fact, in the first phase of the research described in this thesis, some initial attempts were made to model sensor-pavement interaction under different loads by the finite difference method using the Fast Lagrangian Analysis of Continua ($FLAC^{3D}$) program (Itasca Inc. 2005); however, modeling complexity and lack of validation opportunities precluded further pursuit of this line of inquiry. Some of the complexity is described in the following sections.

2.7 Pavement Smoothness Specification for WIM

Pavement surface roughness at a WIM site plays an important role in ability of WIM devices to estimate static axle weights of vehicles in an acceptable range of accuracy since this factor affects measuring the dynamic forces of a moving vehicle.

The American Association of State Highway and Transportation Officials (AASHTO) defines roughness, dynamic axle load and the long and short-range pavement surface roughness (the distances are calculated from the middle of each sensor sets) as follows:

- "Dynamic axle load refers to the component of the time-varying forces applied perpendicularly to the road surface by the tires of any one axle of a moving vehicle",
- "Roughness refers to vertical deviation of a pavement surface from a horizontal reference along a wheel track with characteristics that effect vehicle dynamics, including dynamic axle loads",
- "Short-range roughness refers to vertical deviations of the pavement surface from a horizontal reference within a range of pavement from 2.8 m [9.2 ft] preceding a WIM scale to 0.5 m [1.6 ft] beyond it", and
- "Long-range roughness refers to vertical deviations of the pavement surface from a horizontal reference within a range of pavement from 25.8 m [84.6 ft] preceding a WIM scale to 3.2 m [10.5 ft] beyond it."

AASHTO standardized a procedure for measuring and the long and short-range pavement surface roughness indices (SRI and LRI respectively) at WIM sites. A computer program is employed to investigate the correlation between SRI and LRI and distribution of axle load error levels over the site using simulations of truck dynamic loading. At the last step, the acceptable levels of SRI and LRI will be determined based on the criterion that at those levels of roughness, the WIM system errors of estimations will not exceed the ASTM 1318 recommended guidelines for axle, axle group or gross weight error levels for the specific type of WIM sensor in 95% of the time. The error of estimation is calculated based on the static weight measurement (Equation 1):

$$e = \frac{W_{WIM\ System\ Estimation} - W_{Static\ Scale\ Measurement}}{W_{Static\ Scale\ Measurement}}$$

Equation 1- Error calculation based on the static weight measurment

A background study to this procedure was performed by Karamihas and Gillespie (Karamihas, Gillespie 2004)(Karamihas, Gillespie 2004), who developed SRI and LRI and correlation between these indices and type I WIM error levels {{171 Karamihas,S.M. 2004}}. The models can be used to predict the potential WIM error levels due to pavement roughness. The performance requirements for type I and type II WIM sensors were summarized in Table 2-7. This procedure is used for selecting the site's best place to install the WIM devices in order to achieve the most accurate WIM estimations.

Table 2-7- Performance reqirements for WIM systems for 95% compliance

Load Type	**Sensor Type**	
	Type I	**Type II**
Wheel	±25%	-
Axle	±20%	±30%
Axle Group	±15%	±20%
Gross Weight	±10%	±15%
Speed	2 km/hr	
Axle Spacing and Wheelbase	15 cm	

The standard requires that the specific type of WIM system (e.g. at all CPATT experimental sites only the type II WIM systems were installed) is installed in a location that satisfies the lower and upper thresholds. The values of long and short ranges and also the peak short range (the max value of SRI from 2.45 m ahead of to 1.5 m beyond the system) must not exceed the upper threshold since the upper threshold is the maximum limit that beyond it the site is very likely to produce unacceptable level of estimation error. The best condition is that the site's characteristic stays less than or equal to the lower threshold. Table 2-8 and Table 2-9 show the thresholds for ranges of indices for the type I and type II WIM systems respectively (AASHTO Designation 2006).

Table 2-8- Type I WIM Thresholds for roughness Indices

Range of Roughness Index	Lower Threshold (m/km)	Upper Threshold (m/km)
Long	0.5	2.1
Short	0.5	2.1
Peak short range	0.75	2.9

Table 2-9- Type II WIM Thresholds for roughness Indices

Range of Roughness Index	Lower Threshold (m/km)	Upper Threshold (m/km)
Long	0.9	3.8
Short	1.25	5.7
Peak short range	1.6	6.6

2.8 Modeling the WIM Sensors and the Flexible Pavements

2.8.1 Efforts on Sensor-Pavement Modeling and Verification

Many studies have been done regarding the behaviour of flexible pavements under static or dynamic loads using the finite element method, however very few studies have been carried out concerning the behaviour of the installed sensor itself. WIM sensors measure the dynamic loads which are transferred from pavement to the sensor. Therefore, the interaction between sensor and pavement is of great importance, since the installation environment has a direct effect on the sensor response. Moreover, this response will be affected when any parameters involve in this interaction change, especially in the close environment of the installation.

Flexible pavements are made up of bituminous and granular materials. The term “flexible” refers to the stiffness of asphalt mix and how it transmits axle loads to the underlying pavement layers. The structure of a typical flexible pavement is a multi-layered system consisting of asphalt layers resting on granular soil layers having different material properties. Figure 2-5 shows the pavement structure at the Landfill and Highway 401 sites. In loading time, each lower layer receives the stresses from the upper layer, spreads the stresses out, and passes on the rest to the layer below. Each layer senses the load differently according to its mechanical properties and consequently responds differently. Additionally, the further down in the pavement structure the layer is, the less stresses and displacement it experiences. Hence, the quantity of stresses and displacements change from layer to layer. Designers take advantage of mechanical properties of soil layers by arranging the layers in order of decreasing load-bearing capacity from the surface layer to those below. Therefore, the highest load bearing capacity layer, which is the most expensive one is placed at the top, and the lowest load-bearing capacity which is the least expensive layer, is placed at the bottom.

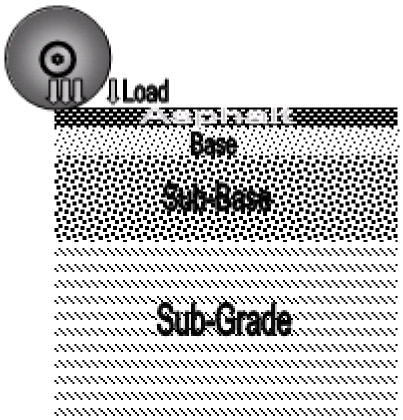
The European Cooperation in the Field of Scientific and Technical Research (COST 323) aimed at “promoting the development and implementation of weigh-in-motion techniques and their applications and to facilitate an exchange of experiences between different European countries”. The COST 323 has been effective since 1993. During the COST 323 action, it emerged that further research on WIM is necessary to develop and improve the accuracy including data structures and format, standardized calibration procedures, new fiber optic sensors and tests of WIM systems in cold and mountainous harsh climates (Gajda et al. 2007). Thus, different MS-WIM arrays were instrumented in France such as the one on Metz-Obrion, which is sited on the A31 motorway, in the southbound direction (Luxemburg-Nancy) on the slow lane. The mean traffic speed at this site was 90 km/hr. The installation consisted of 16 piezoelectric sensors spaced by 1.6 m, which were connected to a Hestia data logger supplied by the vendor. The reason for selecting 16 sensor strips was to gain high accuracy; however, after some months it was revealed that the individual accuracy of the sensors was not in accordance with the expected performances of the sensors. This problem resulted in large errors in auto-calibration of the whole system and, consequently, some significant errors in the WIM measurements and mainly due to the following reasons (European Commission DG VII-Transport 2001):

- Trucks were traveling close to the right margin or changing lane,
- The length of each sensor was too short or very centered in the traffic lane, so that a large proportion of right wheel load were totally or partially outside of the sensor bar.

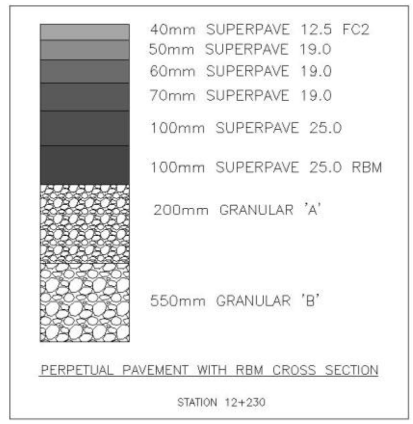
Moreover, there were other explanations for errors as below (Iaquinta et al. 2004):

- WIM electronics, electrical signal conditioning,
- Heterogeneous sensitivity over the sensor length,
- Pavement deflection and dynamic effects,
- Relationship between elastic modulus of pavement and temperature,
- Acceleration or deceleration,
- Installation defects (few sensors replaced),
- Background and inherent instrument noise, and
- Data processing.

The authorities asked the vendor to replace all the sensors; however, it did not change the outcome. It was difficult to determine what happened in the experiments after the A31 site was dismantled. Therefore, it was decided to model the sensors in as much as possible controlled conditions. There are few studies targeted at understanding the behavior of WIM sensors within the pavement material in which they are embedded. Iaquinta et al. (2004) and Labry et al. (2005) had observations of unexpected scattering of the weight measurements along the length of ceramic piezoelectric WIM sensors. The researchers amalgamated lab and in-situ experimentation with modeling of the pavement-sensor system using the finite element method to show the influence of vehicle transverse location on the response of the same sensors.



(a) Landfill



(b) Highway 401

Figure 2-5- Pavement layers at the CPATT sites, (a) Landfill, (b) Highway 401, section 12+230

2.8.1.1 Ceramic Piezoelectric Sensors Modeling and Verification

A team of the metrology and instrumentation service of Laboratoire Central des Ponts et Chaussées (LCPC) performed sensor modeling experiments. Iaquinta et al. and D. Labry et al. were members of the team who collaborated to model the behaviour of ceramic piezoelectric WIM sensors and published the results of their studies in 2004 and 2005 respectively. They planned to inform WIM system users, who utilize piezo-ceramic coaxial cable, to be aware of the effect of vehicle transverse location on the performance of the sensor and enable them to compensate for the errors of measurements, which may occur when this type of sensor is in use. The sensors in both studies use the same piezoelectric coaxial cable (VIBRACOAX®) manufactured by the French company Thermocoax. This sensor is a mineral insulated coaxial cable with a copper tube as a protective covering. The cable is composed of a copper wire running through the center surrounded by compressed piezoelectric ceramic powder. The powder has to be polarized hence the cable is heated up to 400 ^{o}C then a voltage is applied. This voltage orients the electrical charges on the molecules of powder. To stabilize the polarized field the voltage is kept until the cable becomes cool. The ceramic piezoelectric sensor system uses the Vibrocoax sensor in which this coaxial cable is embedded within a U-shape metallic beam filled by epoxy mixture (Figure 2-6). The sensor had low modulus rubber strips on its sides to enhance the vertical stresses on the sensor itself when tire is on it (Guo et al. 2005).

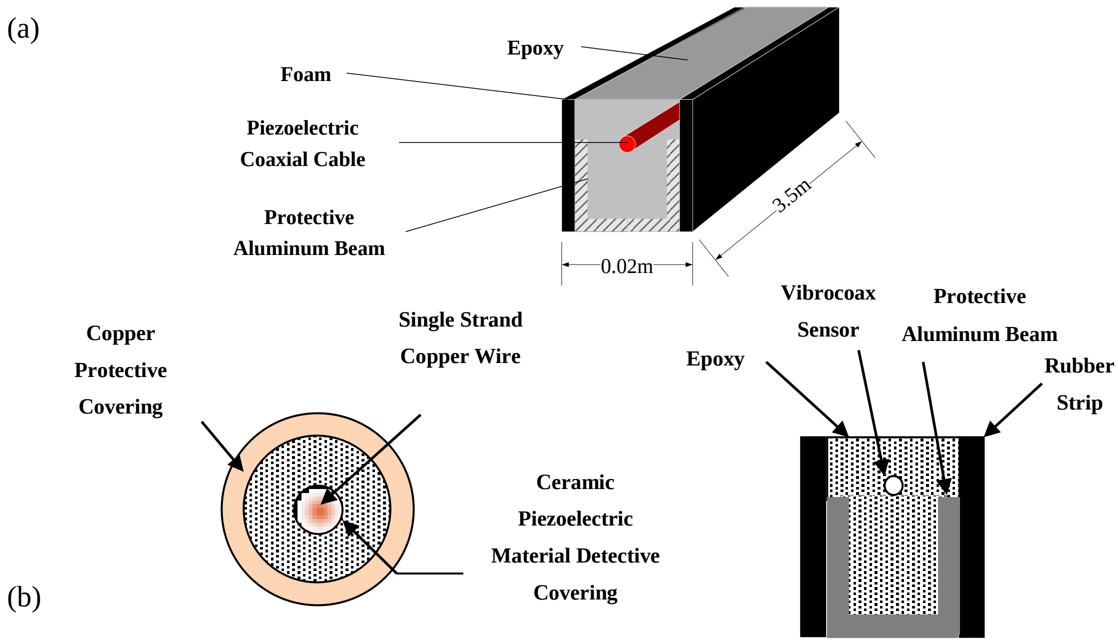


Figure 2-6- (a) Ceramic piezoelectric sensor, (b) Sensor structure (Guo et al. 2005)

Iaquinta et al. (2004) have published one of the studies in this area comprising lab and field trials, to understand the reasons for an unexpected scattering of the weight measurement values along the length of ceramic piezoelectric WIM sensors. The ceramic piezoelectric sensor is one out of two sensors considered by this research. The study confirmed that the location of a tire on the sensor influences the sensitivity especially close to the end of sensor. It means that a single load applied at the end of sensors (at the edge of a lane) will be 30-40% lighter than in their center points. They concluded that with applying an axle load the response demonstrates a maximum decrease of approximately 15-20%, assuming at least one wheel is located close to the center of the sensors. The researchers recommended the study of extrinsic behaviour of the sensors under a real time use environment.

Labry et al. (2005) analyzed the influence of transverse location of a single axle load on the response of the same sensors as well. They combined lab and in-situ experimentation with modeling of the pavement-sensor system using the finite element (FE) method. The FE model showed that the sensor response would mostly be induced by bending moment strains and partly by compressive strains. Forces applied on the sensor (from the center point to the edge, e.g. for the ceramic sensor from zero to 1.65 m distance from the edge) and the response signals were normalized using the value obtained from the center point of the sensor, which was the maximum response (Figure 2-7).

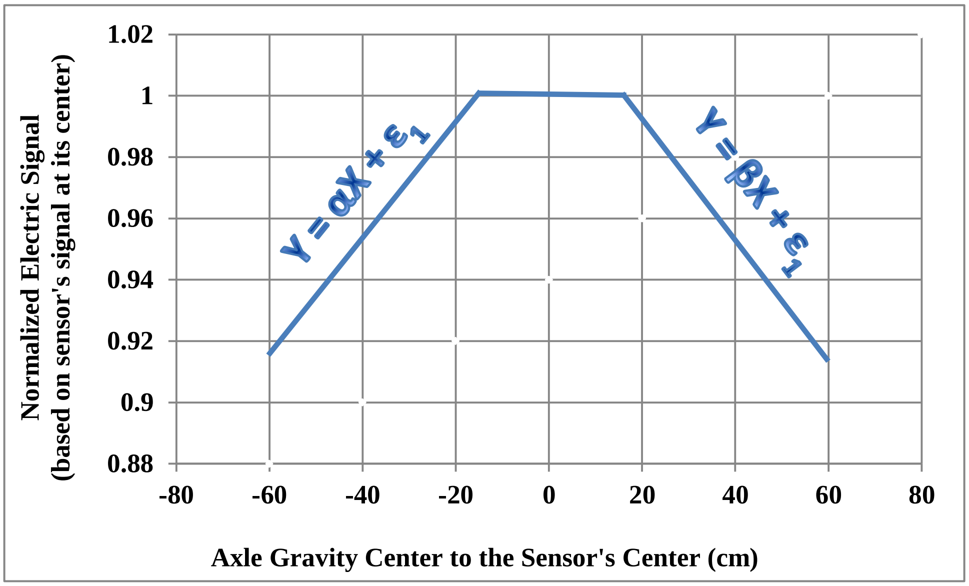


Figure 2-7- The Ceramic sensor model based on location of axle's gravity center

To verify the model, laboratory and field experiments were implemented; however, the researchers stated that due to some technical problems, the field data for the ceramic piezoelectric sensor was not sufficient to verify the results of model. Hence, the ceramic piezoelectric sensors were modeled with correction curves using lab results. The results of this study can be summarized as follow:

- There is a loss of sensitivity close to the edge of ceramic sensors that means an applied load at the end of the sensor will be 30% lighter than it at the center point,
- The researchers concluded that for both types of sensors used in this study, the loss of sensor response proved to be up to 20% along the last of the two 50 cm of the sensor length. The difference between these two types of sensors at this area is that the ceramic piezoelectric sensor illustrates a linear decrease while the other sensor shows erratic variations. From the end of the sensors, the responses increase slightly by 10% to reach the maximum in the center points,
- The loss of response at the edges will affect the accuracy of the system and additionally the auto-calibration results if this method is used for calibration of the system,
- A correction method was developed using a linear factor considering the lateral location of the load on the sensor simulated to correct the response of the ceramic piezoelectric sensor. The slope of the correction curve may depend on the pavement material, rutting and deflection, grout, installation conditions, etc. This slope can be different in some

degree from the one installed in the pavement. The researchers hoped it would work at the site too; however, they did not have adequate field data to validate the lab experiment curve and to evaluate the accuracy of the corrected data. If it worked, the sensor could be used all over its length (Methods of estimating lane position by using diagonally placed WIM sensors have been proposed by other researchers), and

- The results shows that at least with 15 cm distance between the axle's gravity center and the center point of the ceramic piezoelectric sensor, the response will be equal to the applied load with negligible error. Considering a wheel spacing of 2.1 m for an axle, the minimum working length of ceramic piezoelectric sensor would be 2.4 m while the total length of the sensor is 3.3 m.

This study also has some recommendations as follows:

- During the time of deciding a new WIM site, checking the transverse location distribution of the truck paths within the traffic lane is necessary. If the wheel paths are very scattered, the site may not be a proper site for installation.
- Larger scale in-situ experimentation and complementary lab tests on other types of WIM sensors and software will shed light on the behaviour of sensors especially at points close to the center of sensor.
- Moreover, because the study was performed for semi-rigid bituminous pavements, it was recommended to perform the experiment for other types of pavement to assess the quantity of the bending phenomenon. As an example, the bending phenomenon may be negligible in rigid pavements; therefore, the influence of transverse location of load on sensor can be expected to be weak.

2.8.1.2 Efforts on Modeling and Verification of Pavement Response

There are some studies carried out to model the flexible pavements from a design point of view or mechanistic pavement analysis. The studies designed to understand the behaviour of the pavement under climate or loading conditions to predict pavement service life including the CPATT instrumentations at three experimental sites at Highway 401 eastbound (Unpublished work by El-Hakim). Part of these studies utilized FE methods to analyze the pavement layers numerically and consequently verify the results by the data from Falling Weight Deflectometer (FWD) testing, soil pressure cell, soil deformation transducer, moisture sensor, air temperature probe, rain gauge device, etc.(Sargand, Figueroa 2006). The pavement was also instrumented with a weather station to a possible establishment of relationships between the climate and the pavement conditions (Figueroa 2004). In 2003, a research study performed at a quarry near

Roskilde, Denmark in an approximately homogeneous constructed site, which was considered as a suitable situation for pavement predicted response verification (Hildebrand 2003). The experiments were carried out on a halfspace, having a thick layer of fine-grained material over the natural subgrade (layers 1 to 3).Then on the entire pavement system consisting of natural sub-grade, halfspace (layers 1 to 3) and a granular base layer and an asphalt surface layer constructed on the top of layers 1 to 3 (Figure 2-8).

The first layer was instrumented to observe the in-situ strains and stresses for the purpose of the verification of calculated results. The effect of environment on the pavement system conditions was considered insignificant, since a tent covered the unbound material at the test site for eight months. After eight months, layer 4 and the asphalt layer were constructed and the tent was removed. To determine the pavement mechanical properties such as Young's modulus (E), Poisson ratio (ν), dependency to stress, etc., the repeated-load triaxial and Falling Weight Deflectometer (FWD) tests were applied on the test site. The results of repeated-load triaxial and FWD tests showed that the constructed site was homogeneous and isotropic enough for verifying the pavement response and the Young's modulus (E) for natural sub-grade, sandy layers (layers 1 to 3), granular base (layer 4) and asphalt (layer 5) are 100 MPa, 55 MPa, 270 MPa and 5700 MPa respectively. The study concluded that a nonlinear model for the halfspace situation and a dynamic linear finite element model for the multilayer system are the best choices to predict and validate the stress and strain responses in the pavement structure.

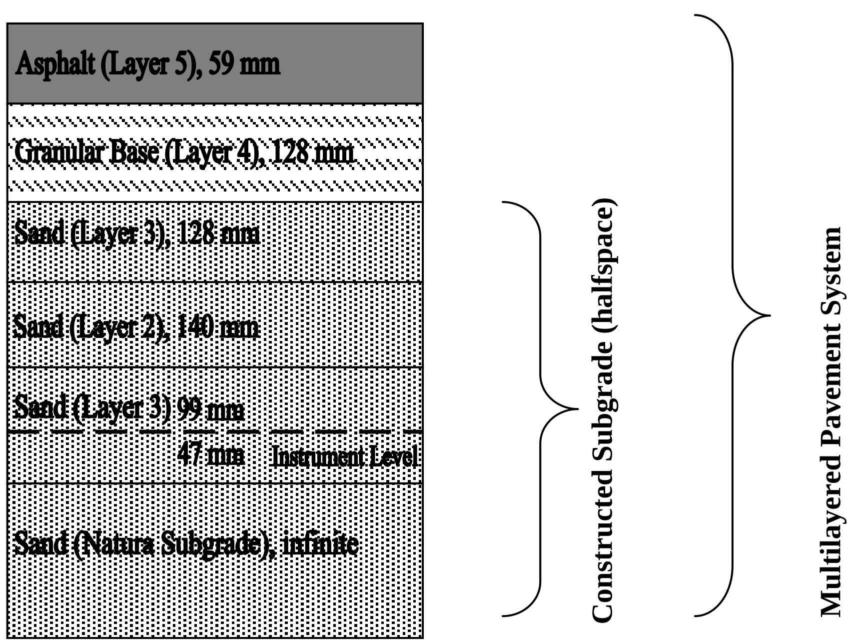


Figure 2-8– Pavement structure at the test site in Denmark (Hildebrand 2003)

2.9 Investigations on Effects of Environment on WIM Sensors' Performance

Since the 1980s, WIM technology has been widely used to improve infrastructure design and enforcement efficiency. The ASTM describes WIM system as "the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle" (ASTM E 1318 2009). Demand for more accurate and reliable WIM sensor systems is increasing due to their capability to provide the managers and decision makers of road systems with up to date data and online measurements of axle loads. To improve the vehicle's static weight estimation in WIM technology, new types of sensors have been developed including Fiber Optic sensors and strain gauges. However, traditional pressure sensors such as piezoelectric sensors, bending plates and load cells still play very important roles in this technology. Piezoelectric sensors' lower cost of installation, hardware and maintenance, make them widely used in various WIM applications. However, they are also known as challenging sensor systems because of various requirements they impose for achieving optimum performance (Middleton et al. 2004).

Accuracy, pavement and sensor installation conditions, data quality assurance, calibration (McCall, Vodrazka 1997), and climate are the most important aspects that WIM users are dealing with. Since these conditions vary from site to site, every installation will have its own characteristics, so that sensors with known general quality of performance will not show the same performance in every installation. For instance, a study of survivability, reliability and accuracy of quartz sensors under highway traffic conditions in Connecticut identified one key failure mode (four sensors failed) in the application of this type of WIM sensor (Larsen, McDonnell May 1998). The mode observed was water penetration to the sensors, which caused to malfunction. During three years of this study, one total replacement of 32 sensors with an improved design of the sensor took place in the second year (1998) by the manufacturer at no cost to the customer, and two malfunctioning sensors found in the third year (2000). Other than the last two malfunctioned sensors, the remaining sensors performed very well during the evaluation time.

In early 2000s, the manufacturer of the quartz WIM sensors improved the durability of the sensor. White et al. (2006) evaluated the accuracy and durability of this sensor in a Portland Cement Concrete (PCC) pavement. The results of this study illustrated that the sensors produced accurate weight data, which met the accuracy specified by the ASTM specifications for the WIM sensor Type I. The consistency of data was acceptable over time, and no sensor failure was observed during the research period. This was in a climate that experienced no freezing.

Several studies have been conducted on ceramic and polymer types of piezoelectric WIM sensors focused on laboratory evaluation of fatigue under wet and dry conditions and two pressure categories: 850 kPa and 200 kPa. Field evaluations of performance have been carried out on Asphalt Concrete (AC) and PCC pavements. The fatigue tests show that under higher pressures, and under both dry and wet conditions, sensors experience changes in output voltage as the number of loading cycles increase. The researchers have not found any voltage changes under the 200 kPa contact pressure (Papagiannakis, Johnston & Alavi 2001a). The field evaluations of performance in both PCC and AC pavements show that durability and repeatability of both types of sensors are acceptable with high signal to noise (S/N) ratios and clear signals. None of the sensors failed during the experiment. In these experiments, the effect of pavement temperature on the voltage amplitude of the raw signal has also been investigated. In polymer piezoelectric sensors the amplitude increased with increased temperature, and in ceramic piezoelectric sensors the amplitude decreased with increased pavement temperature. The authors concluded that the reason for the increase in amplitude is not known whether the reason is a decrease in pavement stiffness or it is the sensors respond differently under different temperatures (Alavi et al. 2001), (Papagiannakis, Johnston & Alavi 2001b).

2.10 Modeling Factors Affecting WIM Sensors and Auto-Calibration Procedures

Improving the vehicle’s static weight estimation with WIM technology is a critical topic in recent years. Many major climate, traffic and pavement design factors affect the estimation accuracy of piezoelectric WIM sensors, while sensors’ structural and material characteristics may cause significantly different performance. A WIM system is calibrated when the sensors’ error of estimations follows a normal distribution with mean zero and constant variance. The factor is adjusted in this situation will be the sensors’ calibration factor (NCHRP 2008).

The National Cooperative Highway Research Program (NCHRP) performed a study to collect information about different calibration practices and investigate the problems and actual procedures the highway administrators, engineers and practitioners were dealing with in their daily business with the WIM sites in the United States. The objective of the study was to investigate the procedures that the state agencies follow for evaluating, calibrating and monitoring the calibration of high-speed WIM systems over time (NCHRP 2008). Some of the major findings, which show significant differences between practices and the ASTM 1318 standard procedure, can be listed as follows:

- Most agencies used only class 9 trucks for on-site calibration while the standard procedure recommends using of classes 5 and 9,
- The standard procedure requires using a test truck with air suspension system on the axle groups while the agencies used trucks with different suspension systems,

- Calibration factors were not specified for different speed bins
- Static load data of traffic stream were used for calibrating WIM systems,
- Experience and knowledge of the agencies' personnel were not properly documented and kept over time
- Agencies developed software to combine manual calibration using on-site test vehicle and WIM data quality control (QC) to gain quality data over time

In cases of using test truck for WIM calibration:

- Only about 25% of agencies considering pavement roughness objectively, even fewer agencies consider structural health condition of the in-situ sensors,
- Approximately half of the agencies run the test trucks with the median speed at the site,
- Approximately 87% of agencies perform on-site calibration calculations,
- Few agencies used the least square method for calibration using WIM and static axle load data and zero-intercept regression approach,

In cases of using traffic stream vehicles of known static weights for WIM calibration:

- Static weights were mostly obtained from permanent scales at truck inspection stations
- Most agencies perform recalibration only when a significant drift was seen. A regular basis (from 1 to 12 months) calibration was carried out by 33% of agencies,
- Using a fixed number of traffic stream trucks, the agencies used an average of 40,
- Using a fixed time period, most agencies used a period of 1 to 4 hours,
- Axle spacing is mostly measured manually,
- Few agencies used the least square method for calculating calibration factors,

In cases of using traffic stream data QC analyses for WIM calibration monitoring

- Many agencies used this method to monitor WIM calibration
- Approximately all the agencies believe that the QC analyses method can identify WIM system problems
- Majority of agencies used class 9 trucks for monitoring WIM calibration by monitoring the steering axle, left and right wheel on steering axle (for type I), GVW for unloaded versus loaded trucks and GVW by speed of truck
- For enforcement purposes the agencies mostly used standard deviation (SD) for steering axle and GVW,
- Most of the agencies monitored the drive tandem axle spacing of 3S2 trucks for axle spacing calibration

The major findings of this study (NCHRP 2008) along with standardized method for quantifying pavement surface roughness at the WIM sites (AASHTO Designation 2006) and the U.S standard for WIM calibration (ASTM E 1318-02), which were discussed in this thesis, were also summarized by Papagiannakis (April 2009).

Efforts on compensating the errors of estimations started with an idea that the load spectra of specific vehicle types over the highways will not change significantly over time and illustrates consistency over a specific site. For instance the most frequent trucks on North America highways, are class 9 3S2 trucks (3-axle tractor, 2-axle Semitrailer) using the Federal Highway Administration (FHWA) vehicle classification. In the 1990s, the gross and steering axle weights of this truck expected to be as displayed in Table 2-10 (McCall, Vodrazka 1997). The table shows that the first and second major peaks in a GVW load spectra should be approximately at 14.5 and 32 tons for unloaded and loaded trucks respectively.

Table 2-10- Expected gross and steering axle weights

Gross Vehicle Weight (GVW)	**Steering Axle Weight**
Less than [14,500 kg (32,000 lbs) ± 3.5%]	3,850 kg (8,500 lbs) ± 3.5%
14,500-31,750 kg (32,000 - 70,000 lbs) ± 3.5%	4,200 kg (9,300 lbs) ± 3.5%
More than [31,750 kg (70,000 lbs) ± 3.5%]	4,700 kg (10,400 lbs) ± 3.5%

Dahlin C. (1992) offered a practical method to calibrate a WIM system based specifically on gross and steering axle weights of the FHWA class 9 trucks. Gross and steering axle weights data produced by the sensors were used in a procedure to control any drifts from an expected norm caused by major parameters such as climate and traffic conditions. The method was for calibration of WIM systems and monitoring that calibration over time.

A study of calibration and adjustments of WIM data in the same year (Gillmann 2005), divided the methods of calibration to Absolute Difference (AD), Percent Difference (PD), and Relative Least Square (RLS). It can be concluded that the PD is a proper method for high-speed WIM calibration procedures.

Ott (1996), discussed the issues the Dahlin's method has, indicating that since the estimated gross weight of 3S2 trucks is a summation of axle's weight estimations, error of GVW estimation are lesser than each axle's estimation error. In addition, the method is based on the distribution of GVW and does not consider other factors. Extensive analyses between the years 1974 to 1983, for the 3S2 trucks' static data (gross and steering axle weights) from 976 sites were also discussed. The results showed that approximately 80% of the sites have bimodal load patterns (including two peaks for unloaded and loaded trucks), 14% uni-modal (loaded), 4% uni-modal (unloaded) and 2% multi-modal (containing more than two peaks).

The authors proposed a method for quality assurance of WIM data. The method is based on constructing confidence interval (CI) for the steering axle static weights compensated for impact of air resistance and for combined variations of steering axle caused by variation within the fleet of 3S2 statically weighed trucks, and dynamic simulation of a typical 3S2 using Vehicle Simulation Model VESYM (Hedrick, Yi 1989) over a specific WIM site. The confidence interval resulted from this method illustrates some advantages as follows:

- The constructed CI is a function of road roughness and trucks speed,
- The method can be customized and integrated into a computer program, and
- An unexpected high steering axle load can indicate that sensors do not work properly.

Finally, for testing this method, four WIM systems including two bending plate and two piezoelectric systems were used.

Evaluation and calibration of WIM sensors have also been investigated using two methods and three types of WIM sensors including, bending plate, piezoelectric and pressure cell systems (Papagiannakis, Senn & Huang 1996). The first method uses a combination of a test truck and VESYM program, which can produce the extent of variation in axle loads of the test truck at a particular WIM site. The second method uses Automatic Vehicle Identification (AVI) device to compare static and dynamic axle weights of vehicles. For implementing this method, the following activities were performed:

- Static axle weights of the AVI-equipped trucks were obtained from two static stations,
- Data from the WIM site, which is upstream from the scales, were obtained,
- A matching process established based on AVI numbers, dates and times of weighing,
- Errors were calculated using percentage difference between static and WIM axle weights, and
- Calibration factors were calculated based on the differences,

The calibrated results illustrated a method of calibration using a portable AVI device specifically designed for this WIM experiment. Successful broad scale implementation is feasible but it will require some agreements and coordination between multiple parties.

The Long Term Pavement Performance Program (LTPP Program) provided procedures to verify the WIM devices, installed in all LTPP’s sites across the US and Canada, are functioning correctly with acceptable calibration tolerances and obtaining good quality load data. The LTPP program offered three major steps for checking WIM devices (Hallenbeck 1998) as follows:

1. Recommendations for checking the calibration of the sensors,
2. Recommendations for quality controls in the field, and
3. Recommendations for quality controls in the office,

Major recommendations for checking the calibration of the sensors include the following items:

- A minimum of two legally loaded 3S2 trucks should be selected,
- Preferably with an air suspension system,
- Must be loaded with GVW between 32700 kg (72,000 lb) and 36500 kg (80,000 lb),
- A minimum of 40 trips over the sensors must be made (20 for each vehicle),
- Passes over the WIM system must be made at highway speeds,
- FHWA classes 6 and 7 (dump trucks) are not proper choices for calibration,
- Shifts from an expected unloaded and loaded peaks in the 3S2 GVW weight pattern must not be more than 400 lb and 8000 lb respectively, and
- Vehicle classification of the WIM system should be checked specifically for vehicles with complex configurations such as long tractor semi-trailer combinations, cars pulling light trailers, number of class 1 (motorcycles) and class 8 vehicles

Major recommendations for quality controls in the field include the following items:

- Count the axles of trucks and check the WIM output,
- Check the axle spacing for 3S2 trucks and passenger cars,
    - 3S2 (Steering axle: 3-4 m, Drive Tandem 1.3-1.5 m, Rear Tandem: 1.2-1.5 m),
    - Car (2.75 m for small car),
- Check WIM's "unclassified" vehicle. If the percentage is less than 5%, the classification works properly, and
- Check WIM's steering and other axle weights to be in the range of site's load pattern.

Major recommendations for quality controls in the office include the following items:

- Check class 1, 8 or unclassified that should be less than 5% of the total traffic,
- Check load pattern of GVW if both peaks shifted. It means there is a calibration problem. If one peak shifted and the other one is correctly placed, it means e.g. there is a large amount of data which are classified but not weighed, and
- The types of goods hauled by class 9 trucks are very useful information, which can be helpful in finding if sensors are working properly. For instance, if there is a mine or a steel or cement plant is upstream or downstream from the WIM site. In such case, 3S2 trucks may be frequently exceeding the maximum legal weight limit (36500 kg).

The LTPP provided also procedures for proving that a WIM device purchased for installation at a site does not produce data under the influence of factors including temperature, vehicle's speed and weight (Wiser 2001). Major recommendations for field data collection are as follows:

- A minimum of two pre-weighed legally loaded 3S2 trucks should be selected, one close to legal maximum load (36500 kg) and the other lighter (e.g. 30000 kg). The load on both test trucks must be stable (e.g. water is not a stable load),
- Preferably with an air suspension system,
- Preferably in a day with temperature variation from morning to night (10 ^{o}C change),
- Must be loaded with GVW between 32700 kg (72,000 lb) and 36500 kg (80,000 lb),
- The speed range should include the normal speeds of approximately 80% of the trucks,
- A minimum of three speeds should be used and each test will start with the fastest and finishes with the slowest speeds,
- A minimum of 4 travels per each temperature and speed class (4*3*3) must be made,
- Sensors should operate under normal procedure. If the normal procedure is operating under auto-calibration, the auto-calibration should be activated during the test
- A minimum of four calibration crew with three radios, and one speed and one temperature guns are necessary for tests
- FHWA classes 6 and 7 (dump trucks) are not proper choices for calibration,
- Record the following data:
    - the axle weights and spacing and the speed of the test trucks,
    - the date and time and the temperature at the time of the test run,
    - the sequence number of the test runs,
    - the calibration factor used by the WIM scale

There are guidelines for traffic data collection and processing including procedures for traffic data collection and calibration of devices (FHWA LTPP Guide 2001), (McCall, Vodrazka 1997).

Southgate, H.F. (2001), Wei T. (2003), Nichols A.P. (2004), Turner S. (2007), Monsere C. (2008), performed several studies specifically for WIM data quality control and quality assurance. For instance, Nichols (2004) proposed a WIM data quality control (QC) method to check axle spacing, and weight accuracies using steering and drive tandem axles of 3S2 trucks respectively. The authors used class I polymer piezoelectric and load cell sensors' data for the study. Quality checks for axle spacing and weight parameters are proposed to be in the range of 1.29 to 1.40 meter (4.25- 4.58 feet) and 3.63 to 5.44 tons (8000-12000 lbs) respectively. The procedure was recommended as an alternative for calibration by a speed radar gun, where this device cannot be used for variety of reasons such as high traffic highways (Nichols, Bullock 2006).The accuracy of weight estimations proposed statistics on left and right axle weights produced by the sensors. The authors explained that WIM system programs majorly use auto-calibration algorithms, which compensate the estimations based on bins containing temperature and weight classes as follow:

- Temperature bins including (0-10), (10-20), (20-30), (30-40) degree of Celsius, and
- GVW bins including (Less than 18 tons or 40,000 lbs), (between 18 to 27 tons or 40,000 to 60,000 lbs), (More than 27 tons or 60,000 lbs).

The authors also recommended the future study on developing an auto-calibration program, which can use continuous temperature change to allocate better compensations for estimations and produce results with less oscillation. They concluded that temperature, water penetration to sensors and wires and sensor malfunctions are major sources of error in the sensors outputs. Temperature itself can cause piezoelectric sensors produce wrong estimations in two major ways. First, by changing the temperature stiffness of pavement will change e.g. by increasing the asphalt pavement temperature the stiffness of pavement will decrease. Therefore, the sensor measures part of an axle load pressure and the resulted weight is estimated less than the actual load (Southgate 2001). Second, by changing the temperature the piezoelectric sensors produce charges, which can be explained by the pyro-electric effect of sensors' sensing elements, e.g. by increasing the temperature; piezoelectric sensors produce positive charges, which result in overestimating the axle load. There is a lack of study specifically on major effects of temperature on the piezoelectric sensors, and to characterize these effects on sensors' estimation accuracy.

Inconsistent performance of piezoelectric WIM systems was explained in a study published in the fifth International Conference on Weigh-In-Motion (Jacob 2009). Burnos P. (2008) worked on compensation factors affecting the WIM system accuracy using two methods of compensation presented and compared including auto-calibration and temperature compensation. It is likely that the inconsistency in performance of piezoelectric WIM systems is because of temperature changes and aging of the sensors. In this paper, the WIM sensor type and the auto-calibration algorithm were not clearly identified and explained. It seems that the research is based on data from 16 polymer piezoelectric sensors, 8 loops and two temperature sensors installed on the road 81 in Gardawice, Poland. The steering axle of a five-axle truck (two-axle tractor, three-axle semitrailer) used as a reference axle weight. The truck is not classified by the FHWA classification. It can be concluded that the auto-calibration procedure, which uses the steering axle load of the site's characteristic vehicle, has consistency in application and need high volume of characteristic vehicles. Temperature correction compensates each weighing result; however, it requires that the WIM system to be pre-calibrated and temperature characteristic of the WM site to be investigated.

There is also a lack of a study, which incorporates weight, temperature and speed to edit the WIM data at the time of occurrence especially focusing on the less expensive piezoelectric WIM sensors. Most of the proposed weight calibration procedures focus on monitoring the steering axle load of 3S2 trucks to track any drifts from an expected norm during a period. For instance, a recent study (Nichols, Cetin 2007) proposed a method to fit two or three normal distributions to the actual load distribution obtained from a WIM site rather than interpret the peaks of loaded and unloaded trucks in the gross weight load spectra, and monitor them over time. The means of normal distributions roughly matches the peaks of the load frequency, which can normally be seen for unloaded, loaded and medium loaded 3S2 trucks. This method also requires a proper time to adjust and update a calibration factor.

Generally, the amount of time required for the adjustments depends on the volume of characteristic trucks on a specific site, which can be between one to four hours in high volume roads. Therefore, there will always be a delay in obtaining a proper calibration factor for adjusting the weight estimations. In a most recent patented study, an auto-calibration procedure has been designed for WIM sensors at static scales (Susor 2009). The procedure takes advantage of devices such as speed and height detectors, camera, Radio Frequency Identification (RFID) transmitter and receiver to record WIM data and use the associated static weight of trucks for analyses in order to update the calibration factor of WIM station at the static scales. However, considering that the static axle weights of trucks are readily available at the static station, this procedure will still need enough time to check whether the last calibration factor has changed significantly and to update the calibration factor.

2.11 Summary and Discussion of Research Needs

According to the literature review, research on the effects of major climate, pavement and traffic conditions on the piezoelectric weigh-in-motion sensors estimation accuracy is vital to improve performance of the sensors. Many studies were carried out on different WIM technologies and proposed multiple calibration methodologies. However, there is still need of exploring the effects of temperature, weight and speed on specific low cost, piezoelectric WIM devices in order to develop more cost effective technology for users.

The acceptable estimation procedure of the least expensive WIM sensors is very dependent on the auto-calibration process, which is proprietary to the vendor and cannot be accessed by a user to construct a custom-made algorithm for the user's region and site of interest. Accuracy problems reported from many WIM users and lack of knowledge about the auto-calibration procedure of WIM sensors can result in unreliable data. The CPATT research team decided to confront the problem by first investing in installation, calibration and data gathering of different piezoelectric WIM sensors in two different flexible pavement designs at the Landfill and Highway 401 sites. The next step was to model the least expensive piezoelectric WIM technology against loading and climate conditions.

This research study intended to investigate the effect of air temperature, and vehicle's weight and speed on the estimation accuracy of polymer piezoelectric sensors. The sensors were installed on both CPATT experimental sites, which have potentially different characteristics in terms of pavement design and traffic conditions. This will help explore alternative and transparent procedures for the WIM sensor system and improved benefits of least expensive technology. To finalize the target of modeling the sensor system, the research team communicated with modelers and experts and used feedback from PhD committee members who assessed the original proposal for this research.

Chapter 3
Methodology

A consistent methodology was used to both test sites, which are located at the Waste Management Division of the Region of Waterloo at 925 Erb Street West, Gate 1 (Figure 3-1) including different pavement sections (Figure 3-2) and on Highway 401 between exits 238 and 250 near Woodstock, Ontario (Figure 3-3). The methodology developed for statistical modeling is based on the factorial experiment method with which the sensitivity of sensors to the specific climate and traffic parameters were investigated. In the next step, extensive statistical analyses focused primarily on regression and frequency analysis were used to provide the basic knowledge for recommending compensation factors for improving estimation accuracy of sensors. Descriptive statistics of some data were also used in later sections.

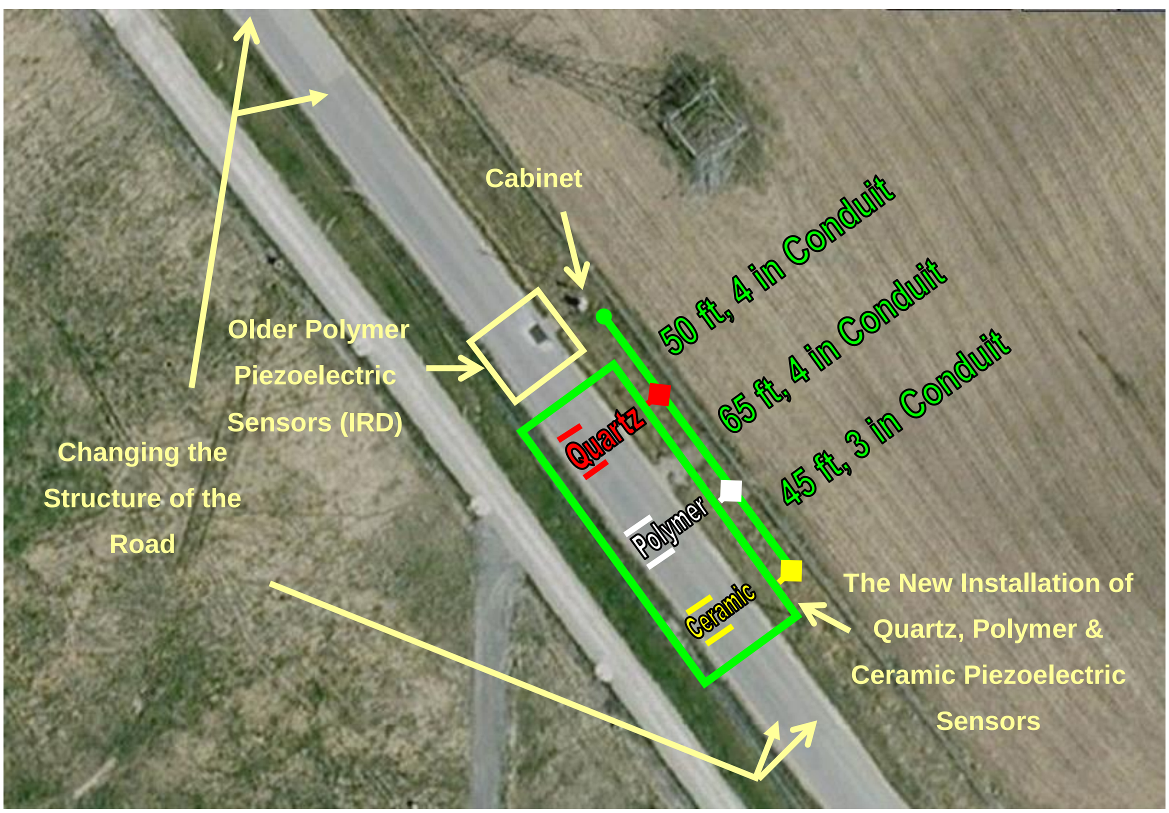


Figure 3-1- The Landfill site at the Region of Waterloo (Google Maps Canada 2011b)

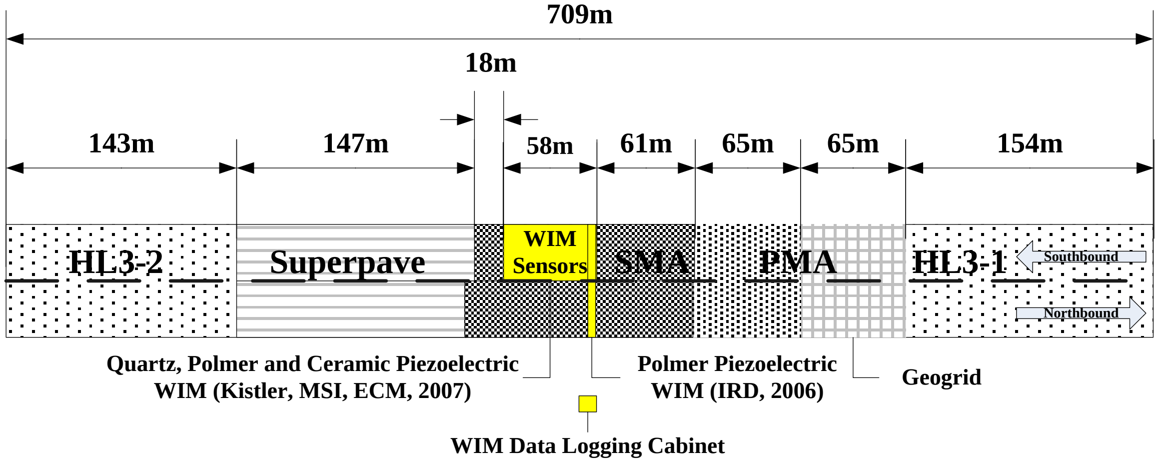


Figure 3-2- The Landfill site including hot-laid 3 (HL3), polymer-modified asphalt (PMA), stone mastic asphalt (SMA) and superpave sections (Tighe, Falls & Doré 2007with minor corrections)

Figure 3-3- The Highway 401 site (Google Maps Canada 2011a)

3.1 Preliminary Stage

3.1.1 Sensor and Equipment Procurement

Considering the situation of WIM sensor installations, the research team decided to invest on installation of different piezoelectric WIM sensors. Equipment, tools and material required for installation were listed to be bought or rented according to the suppliers' recommendations. The base line of $500 was decided to be a separator between buy and rent items. Therefore, most of the equipment and tools, which cost lower than the base line, were decided to be bought and rest of them booked for the time of installations.

3.1.2 Installation of WIM Sensors

In September 2003, a piezoelectric WIM system was installed on the two-lane stone mastic asphalt (SMA) section of the test track at the Landfill site. The system mainly consisted of two polymer piezoelectric class II piezoelectric sensors and two inductive loops on each lane, and a roadside cabinet for the WIM electronics. From May to June 2006, after a detailed field survey found that the sensors on the southbound lane were damaged, the site was rehabilitated to a stable structure and the damaged sensors were replaced. In September 2007, the MS WIM system was installed on the southbound lane in order to achieve higher accuracies, to take advantage of the upstream static scale, to gather the loaded trucks data, and to compare different technologies. Table A. 4 and Table A. 5 (Appendix A) illustrate the workforce and schedule of tasks for the different installations respectively. The systems included quartz, polymer and ceramic piezoelectric sensors at the site near to the previous set. The site was investigated again according to the ASTM Standards document (ASTM E 2415 2005). The site characteristics substantially satisfied the standard requirements. However, the average gradient at the Landfill site is 2.19% and is very close to the limit. ASTM emphasizes that, "the longitudinal gradient of the road surface for 200 ft (60 m) in advance of and 100 ft (30 m) beyond the WIM system sensors shall not exceed 2%" (ASTM E 1318 2009).

In 2011, the CPATT installed the second MS-WIM system on one out of the three new experimental sites at Highway 401, which has a perpetual pavement design (Hashemi Vaziri et al. 2011). All sites had already been instrumented with asphalt strain gauges (ASG), earth pressure cells (EPC), moisture probes (MP) and Thermistor strings (TS). The new WIM system at this site includes one set of quartz and one set of polymer piezoelectric WIM sensors with the loop-sensor-loop configuration.

3.1.2.1 WIM Sensors System Configurations

The configuration with which the ECM® Hestia® system is able to operate the CPATT's type II piezoelectric WIM sensors is sensor-loop-sensor. Figure 3-4, shows this configuration for the quartz sensor installation at the Highway 401 site, which is the same configuration was used for all WIM systems at CPATT WIM sites. At the CPATT sites, the WIM sensors were installed in two rows to have the benefit of improved accuracy by averaging the sensor system outputs. The as-built drawings of installations at both WIM sites (Figure 3-5 to Figure 3-8) are as follows:

- The quartz piezoelectric sensors (in 1.00 m and 0.75 m lengths) were installed in the 3.5 m width lane at both sites (two of each length per lane).
- The polymer piezoelectric sensors (3.5 m in length) were installed at both sites, and
- The ceramic piezoelectric sensors (3.5 m in length) were installed just in the Landfill site

The length of the WIM installation at the Landfill site is 58 m and on the Highway 401 site, it is approximately 10 m.

3.1.2.2 Installation Details

Slots for installation of sensors were cut by pavement saw equipment using diamond blades. The asphalt material between cuts was removed with an electrical impact chisel. Each sensor's slot was cleaned with an air blower. Finally, the slots were all double checked to be dust free and completely dry before grouting. The sensors were embedded into slots with specific grouts supplied by the vendor. After the grout were set, the surface of the sensors or grout-filled slots were smoothed and flushed with pavement along the slot length using a trowel or putty knife. In the case of quartz piezoelectric sensors, after the grout was cured in the slot, the surface of the filled slot is ground and sand-belted since the sensors' surface must be fully flush with the pavement. The details of installation for each WIM sensor are discussed below:

- Quartz WIM Sensors – The sensors consist of an Aluminum alloy profile comprising quartz-sensing elements fitted inside of the profile under preload (Figure 3-9 and Figure 3-10). In both types, the quartz discs were mounted in the profile (one element per 5 cm), which allows the measurement of vertical forces, such as wheel loads (Cornu August/September 2007). The quartz sensor manufacturing video demonstrated how quartz elements are inserted in the Aluminum alloy profile (Kistler Instrumente AG n.d.). According to Calderara (1996), the profile including quartz discs is packed by applying a lateral force to the profile. Therefore, the elements are pretensioned.

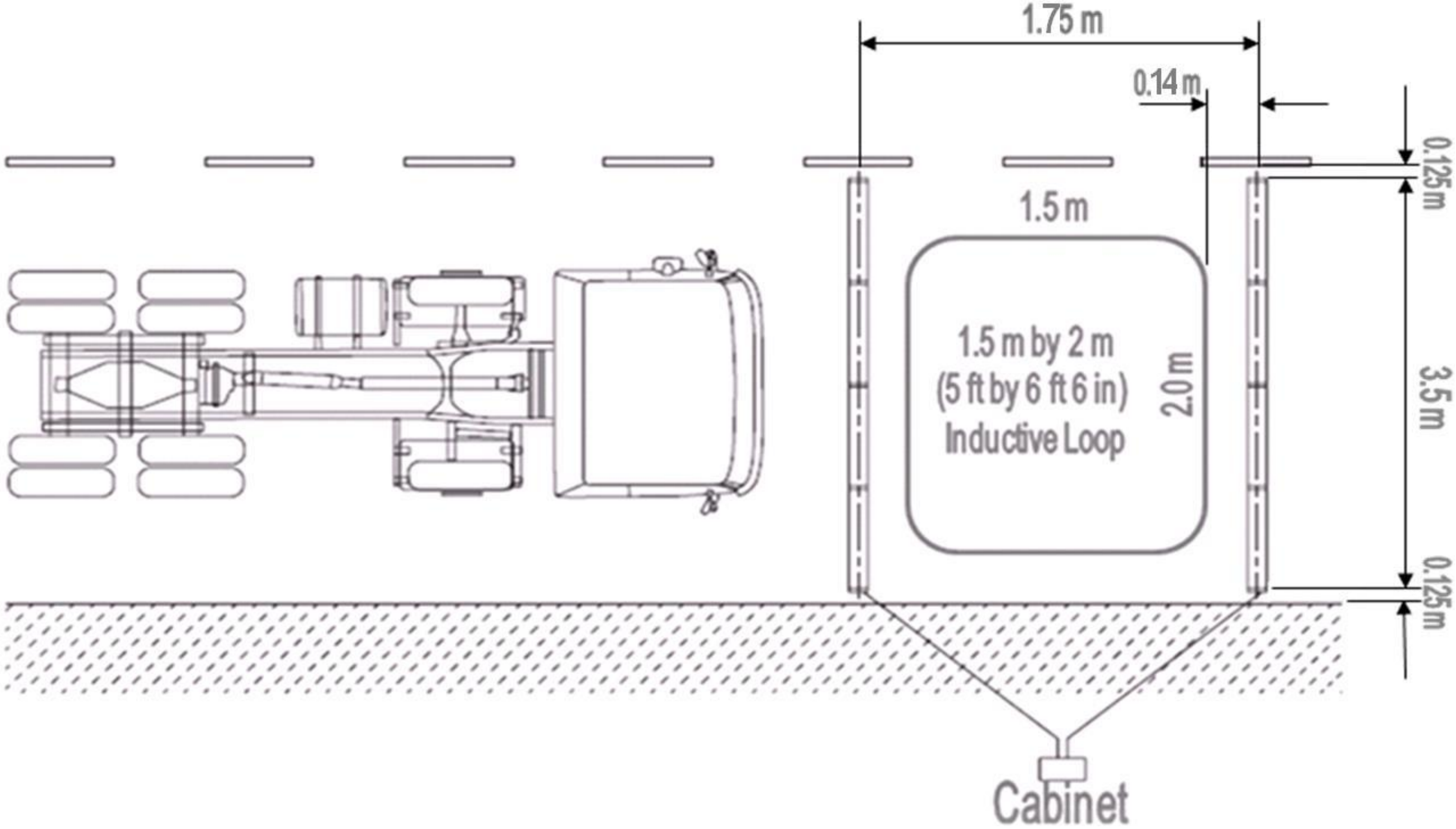
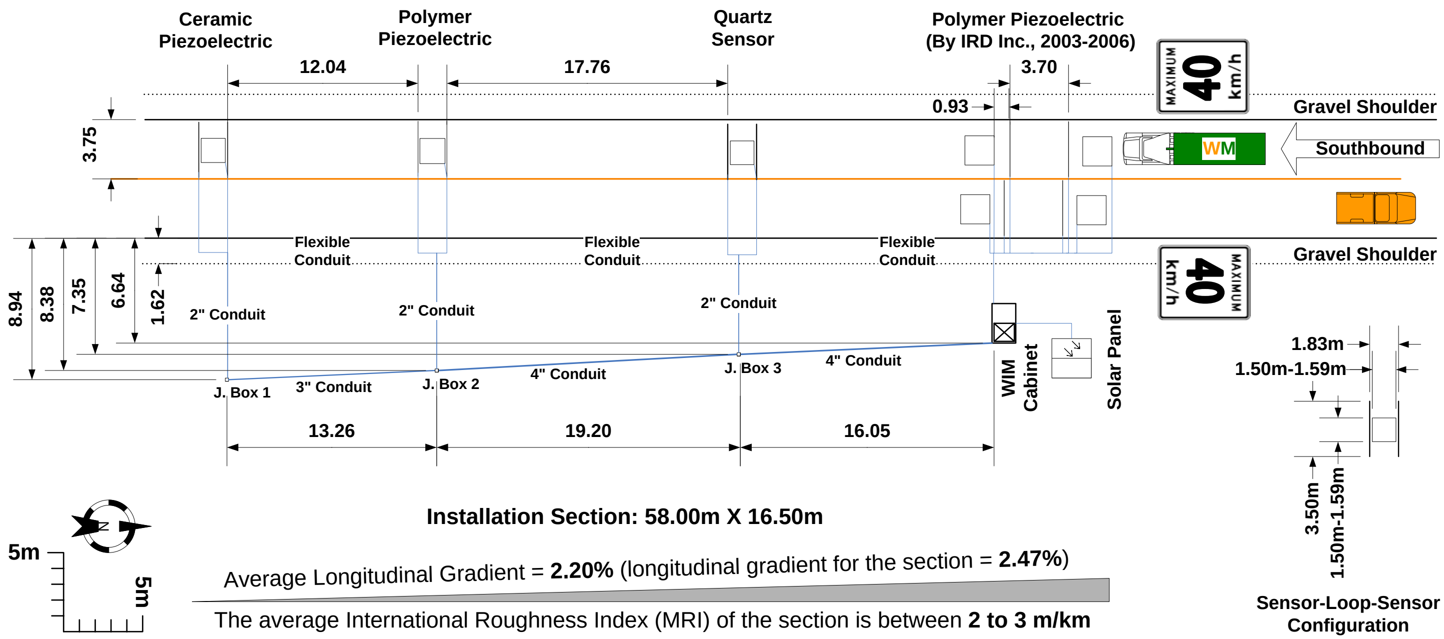


Figure 3-4- Typical installation configuration and details for ECM® Hestia® WIM system



Weigh-In-Motion Sensors Installation Drawings

At:
925 Erb St. W., Waste Management Division, Landfill

Materials used for this installation were as follows:
Sand (backfill, 44 * 30 kg), PVC Flexible Conduit½" (60') and ¾" (120'), PVC Rigid Conduit 2" (2 * 10'), PVC Rigid Conduit 3" (5 * 10'), PVC Rigid Conduit 4" (12 * 10'), PVC Rigid Elbow 2" (3), PVC Rigid Elbow 3" (2), PVC Rigid Elbow 4" (5), Ground Wire (600'), Electrical Tape (Tempflex, 7 colours, 18), Sealing Glue (PVC Cement, 1 can), PVC Junction Box 8"*8"*4" (3), tools (according to the supplier's list), equipment (according to the supplier's list)

This installation took place from Friday 21st to Friday 28th September 2007. ECM was installed on Saturday 22nd, Kistler (Each row includes 0.75 m close to the shoulder, 1 m, 0.75 m, 1 m) and MSI on Monday 24th and Loop installations on Tuesday 25th. On Wednesday 26th, conduit installations were finished and on Thursday 27th electrical works in the Cabinet, and initial tests of the sensors and training were accomplished. On Friday 28th, backfilling, cleaning the site, marking the conduit by rocks and paint and finishing the leftover works such as sand-belting the Kistler sensors and grouting the wire cuts on the pavement. During these days, details of work have been photographed and filmed for maintenance purposes. Total hours for this installation was 505 hrs.

Note: All objects are to the scale but Solar Panel, Test Car, lines of Road and Shoulder, Traffic Flow arrow and the Traffic Sign, Also the units are in meters

IRD Sensor Spacing: 3.70m Loop: (1.85*1.85)m Sensor Slot: 40mm Loop &Sensor: 0.9m	Kistler Sensor Spacing: 1.83m Loop: 1.50m*1.50m, Sensor Slot: 75mm MSI Sensor Spacing: 1.83m Loop: 1.59m*1.59m, Sensor Slot: 20mm ECM Sensor Spacing: 1.83m Loop: 1.53m*1.53m, Sensor Slot: 50mm	Overall Sensor Dimensions Loop: (1.5m to 1.59m)^2 Sensor Rows Spacing: 1.83m Slope (Installation Part): 2.47% Sensor length 0.75m, 1 m and 3.5m SB width: 3.75m Slope (Longitudinal profile): 2.22%	REV 01 July 2008
SCALE 1:333	VISIODOCUMENT	SHEET 1 of 1	

SHAHRAM HASHEMI VAZIRI

Figure 3-5- The layout of WIM sensor systems at the Landfill site

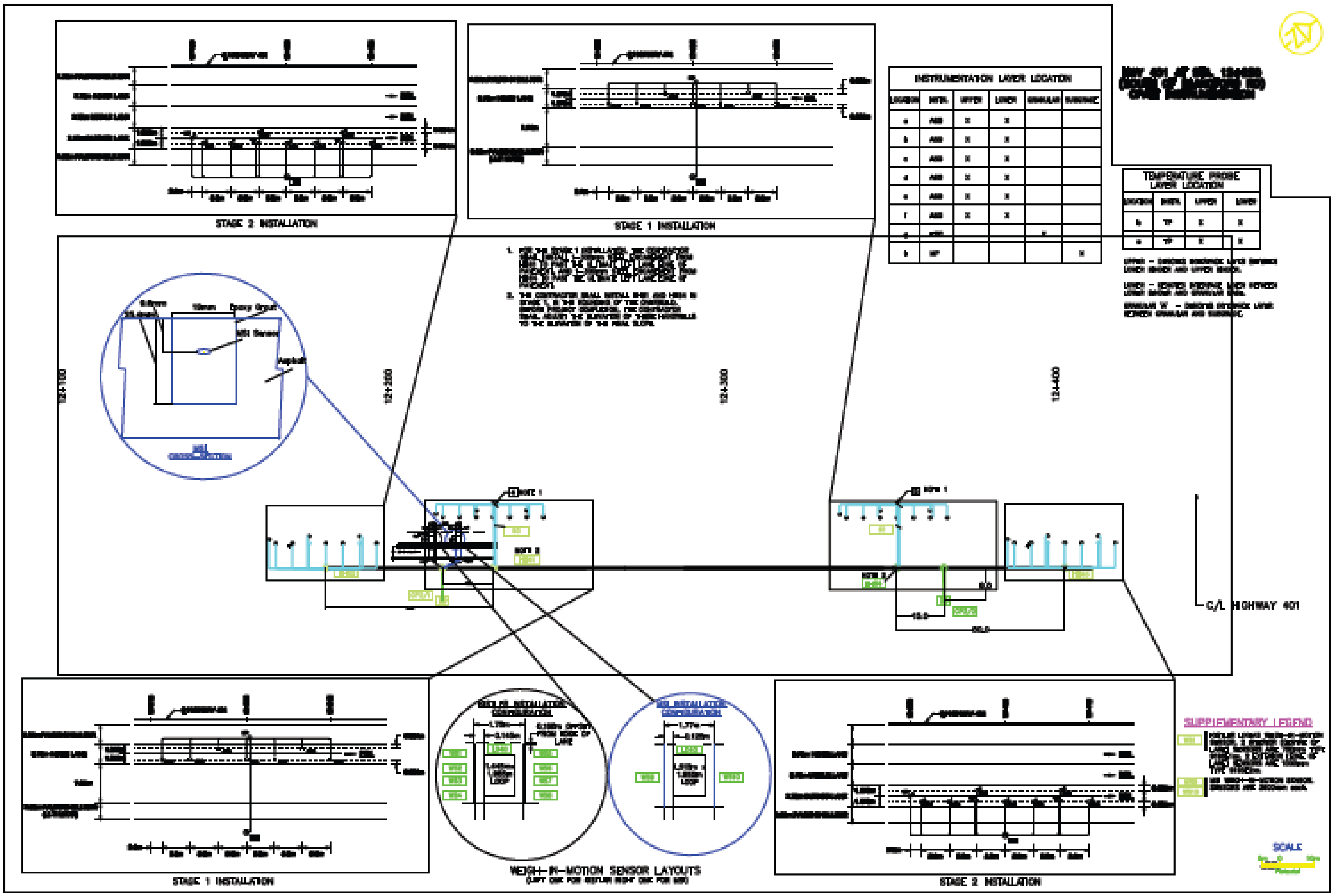


Figure 3-6- CPATT Instrumentation including WIM sensor systems at the HWY 401, sections 12+230 and 12+350

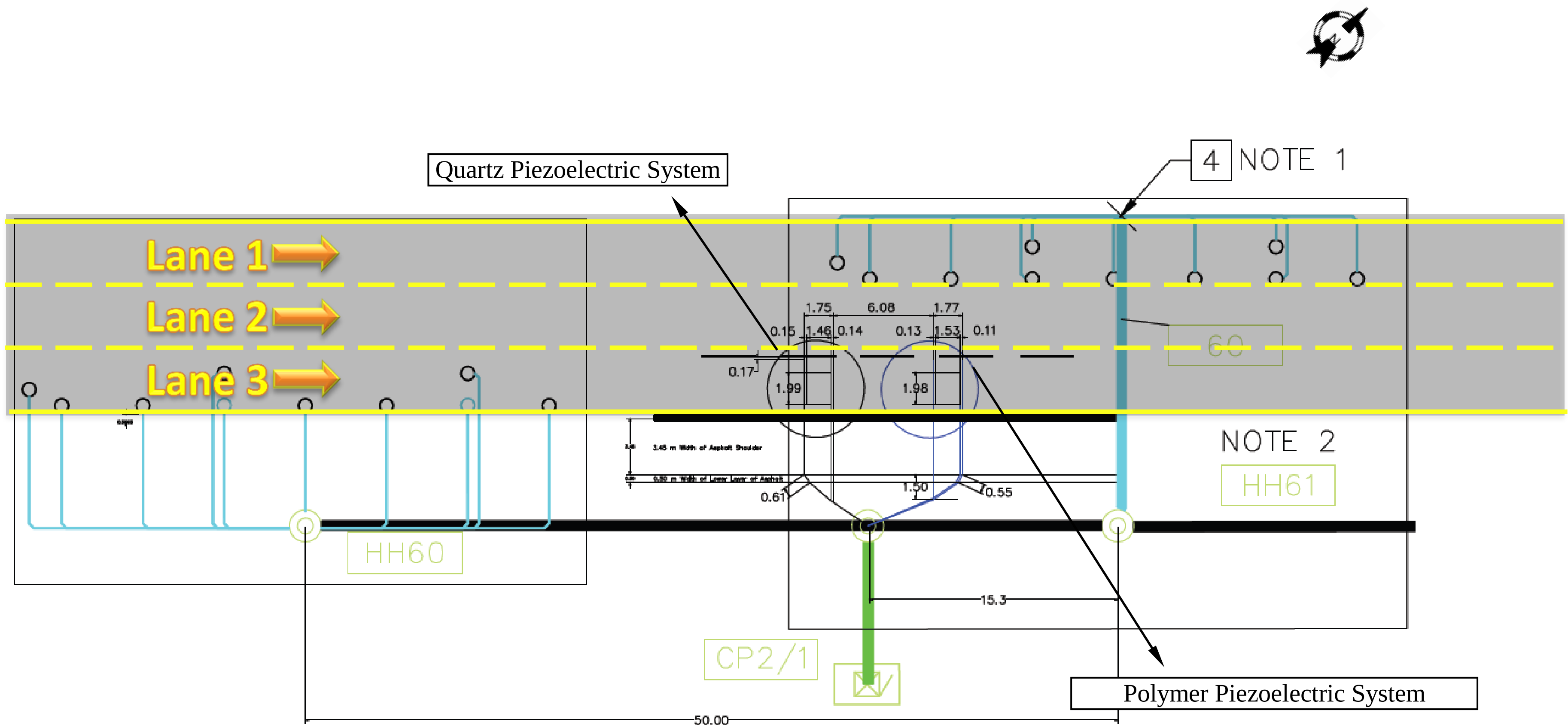


Figure 3-7- CPATT Instrumentation including WIM sensor systems at the HWY 401 site, section 12+230

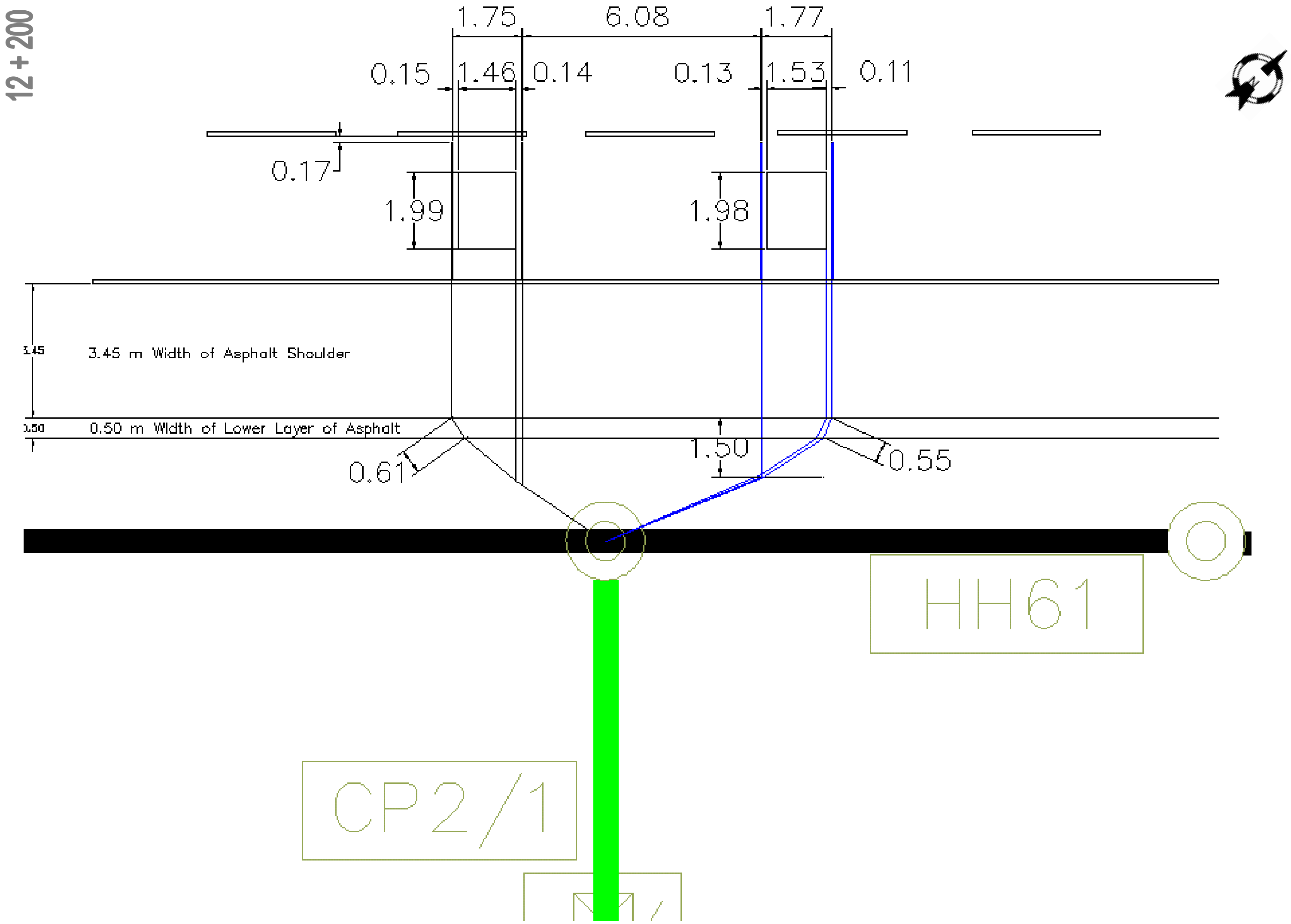


Figure 3-8- The layout of WIM sensors systems at the Highway 401 site, section 12+230 (the polymer piezoelectric set is at the right side)

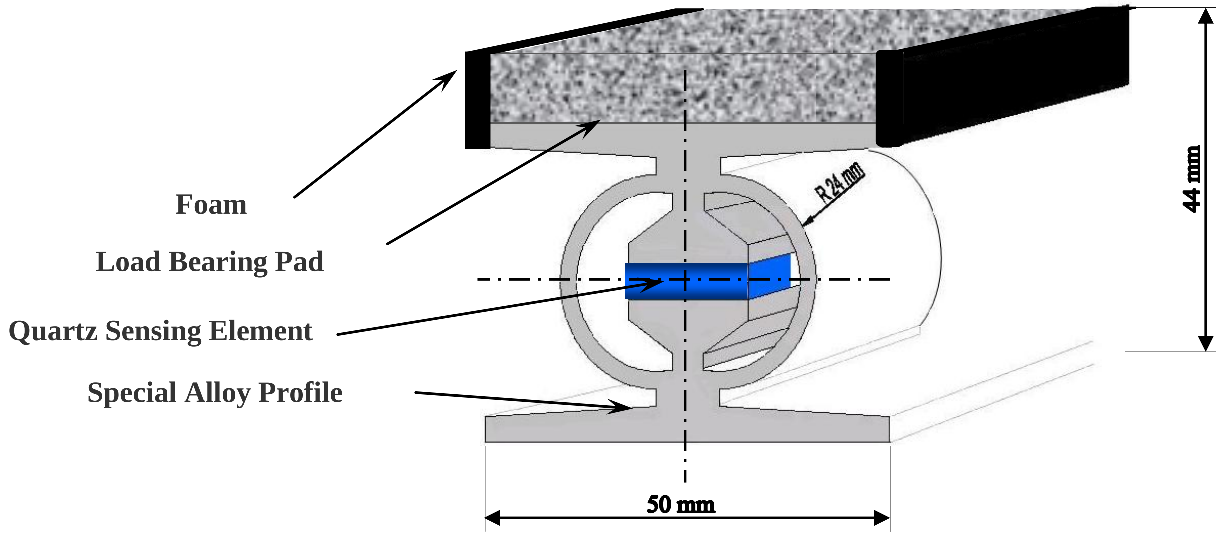
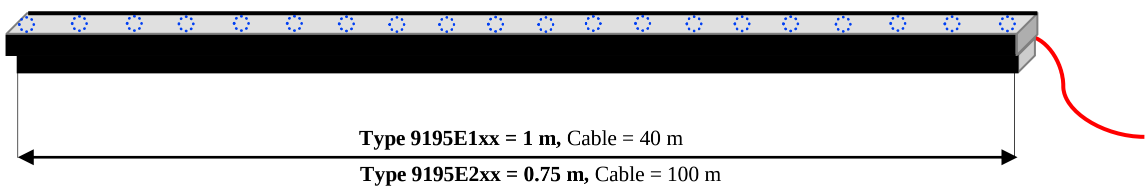
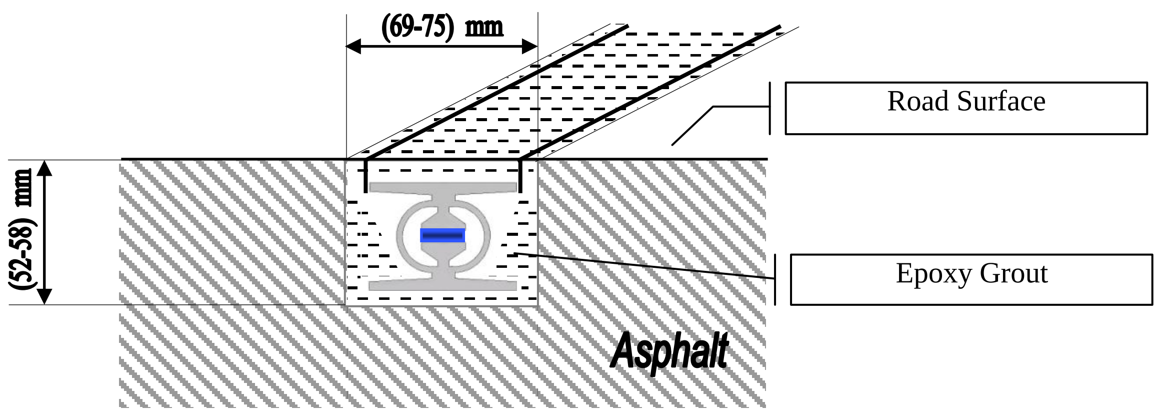


Figure 3-9– Lineas® sensor (drawn by author based on Kistler Instrumente AG 2004a)



(a)

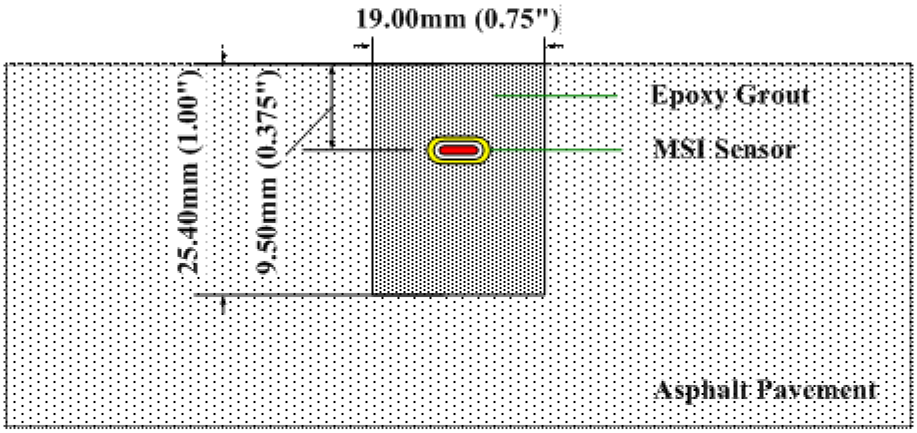


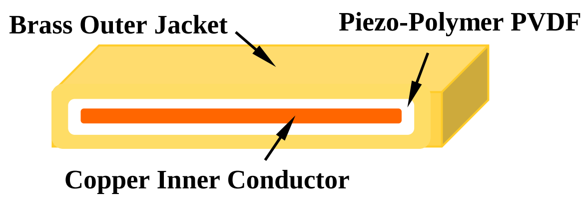
(b)

Figure 3-10- (a) Quartz sensing elements in a 1 m sensor (b) Cross-section and installation details (drawn by author based on Kistler Instrumente AG 2004b)

- Polymer piezoelectric sensors (IRD or MSI) – The installed sensors called Roadtrax® BL (Brass Linguini®). The sensor is 3.5 m in length and flexible with a visible bare brass sheet cover of piezoelectric cable (Figure 3-11).

(a)





(b)

Figure 3-11- (a) MSI® installation details (drawn by author based on IRD Inc. n.d.)

(b) Sensor structure (drawn by author based onMeasurement Specialties)

- ECM® Piezolor®- This sensor is a mineral insulated coaxial cable called Vibracoax, which is encapsulated within a U-shape metallic beam filled by an epoxy mixture. The sensor has low modulus rubber strips on its sides to enhance the vertical stresses and is embedded into a slot filled by a specific epoxy mix (P5G) (Figure 3-12).

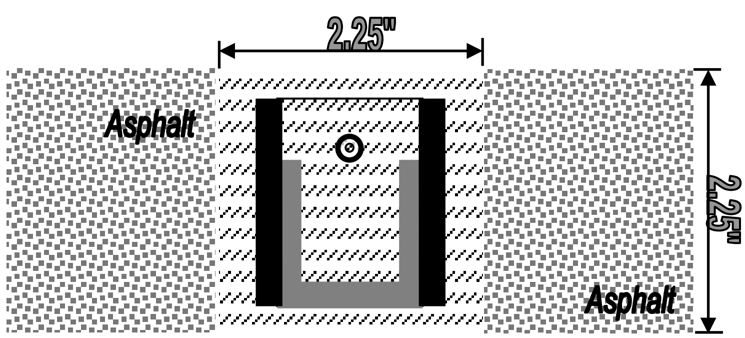


Figure 3-12- Ceramic piezoelectric sensor installation details (drawn by author based on Electronique Contrôle Mesure (ECM) n.d.)

3.1.3 Calibration

3.1.3.1 Pre-calibration Efforts

After the sensors were installed, pre-calibration of sensors was carried out to learn about the sensor responses and to organize effective calibrations according to ASTM standards. The pre-calibration was performed using the CPATT van, which has two axles and the gross weight of 3.0 tons. The research team decided to use manual calibration for the whole system for study purposes. However, the vendor's auto-calibration process remained an option, especially for collecting reliable load data for updating seasonal load spectra for the Ministry of Transportation Ontario (MTO) and to evaluate the performance of this sensor under the vendors' auto-calibration process. Field surveys for measuring the pavement surface conditions at the Landfill site was also performed before and after the installation of the MS-WIM system (Appendix A).

3.1.3.2 Calibration

It was decided to use both manual and vendor's automatic calibration procedures to evaluate the sensor systems performance. In the manual calibration process, the fixed set of calibration factors are found by driving pre-weighed vehicles over the sensor sets. In the manual calibration process, calibration factors are adjusted to achieve the best performance of sensor sets at a particular set of climate and traffic conditions. The main difference between auto and manual calibration processes is that in the manual method, the user defines the factors according to specific conditions of the user's test site, while in the auto-calibration process the WIM system software determines the proper factors for the class of vehicle for the site. In the auto-calibration process, the factors are periodically updated according to procedures that are either not well demonstrated by the vendors or are proprietary and not shared. Since every site has its own characteristics, such as climate, pavement surface, traffic volume, sensor type, speed of vehicles, etc., the auto-calibration process is not able to reliably adjust factors for some sites. In such cases, users may prefer to apply a manual process to calibrate the sensors. Figure 3-13 shows the simplified manual and auto calibration processes for the CPATT test sites.

The following sections compare performance of the Landfill site for manual and auto-calibration approaches. The intent was to gain some insight into the advantages and disadvantages of each approach. Figure 3-14 and Figure 3-15 illustrate the summaries of the tasks were performed at the Landfill and Highway 401 sites respectively.

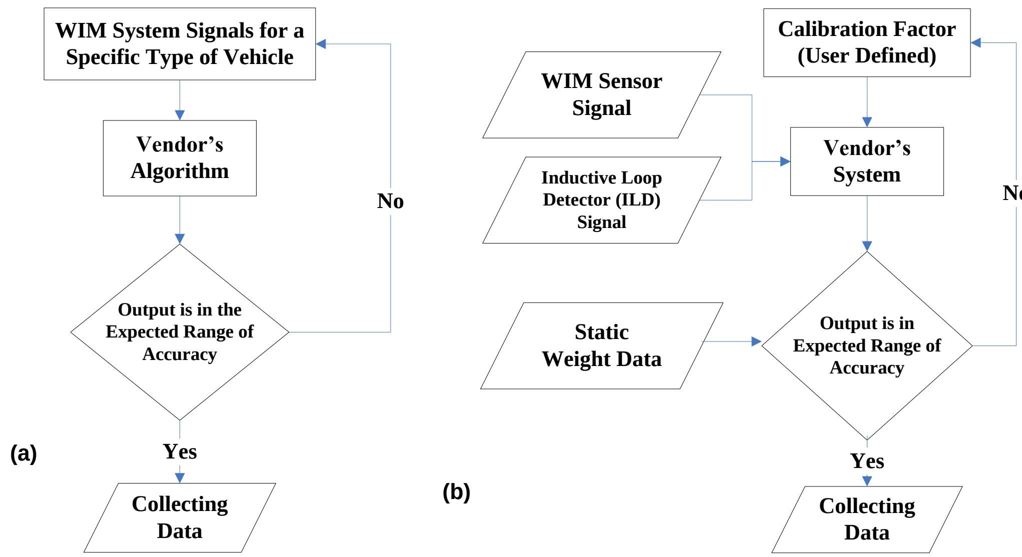


Figure 3-13- (a) Auto-calibration (b) Manual calibration process, for the CPATT test site

3.1.3.3 Manual Calibration Procedures

Calibration of the WIM sensors are divided to two major parts including axle weight and axle spacing calibrations. When both procedures were performed correctly, the sensors' estimations on gross and axle weights, length, wheelbase, axle spacing and speed are considered reliable. The manual calibrations for all sets of sensors at the CPATT sites were performed according to ASTM E1318. The ASTM standards have guidelines for manual calibration of WIM sensors including recommendations for calibration vehicle, speed and transverse location of vehicle over sensors as follows:

- The Class 6 FHWA garbage trucks at the Landfill site (Figure 3-16), and the class 9 FHWA five-axle truck at the Highway 401 site, are the most frequent vehicles traveling over the sensors (Figure 3-17). However, because of resource constraints the CPATT's class 3 Dodge Sprinter van (Figure 3-18) was specified for calibration at both sites. Therefore the static axle weights of the van was used as a reference weight,
- The minimum, maximum and average speeds of the vehicles on the landfill site are assumed to be 30 km/hr, 60 km/hr (minimum and maximum speeds should have 30 km/hr difference according to the ASTM standards) and 50 km/hr respectively. For the Highway 401 site, the average speed is 100 km/hr, and
- Three sets of path runs were considered for manual calibration (Figure 3-19) as Path run1 (tires are close to right-hand edge of lane), Path run 2 (tires are on the main wheel path) and Path run 3 (tires are close to yellow line on left-hand edge of the lane).

ID	Tasks at the Landfill site	Start	Finish	Duration	Task Notes
1	**Manual Pre-calibration: Spotty Limited Data**	01/01/2008	30/04/2008	17w 2d	A few waveform recordings
2	**Manual calibration : Interrupted data supply**	01/05/2008	30/05/2008	4w 2d	
3	**Auto-calibration (ceramic and polymer piezoelectric sensors): Continuous data supply**	02/06/2008	30/09/2008	17w 2d	Request for static weight data from Waste Management, (Jan. 2008 to the end of May 2009)
4	**Auto-cal procedure deactivated: Continuous Data Supply**	01/10/2008	25/09/2009	51w 3d	Auto-cal procedure remained activated only for the polymer piezoelectric sensor system at the Landfill site (unknown reason)
5	**Static data conversion (Jan. to Nov. 2008)**	01/10/2008	13/03/2009	23w 3d	Auto-cal procedure remained activated only for the polymer piezoelectric sensor system at the Landfill site (unknown reason)
6	**Preliminary matching file: (Jan. to Nov. 08)**	01/10/2008	31/03/2009	26w	Auto-cal procedure remained activated only for the polymer piezoelectric sensor system at the Landfill site (unknown reason)
7	**Manual Re-calibration: Continuous Data Supply**	04/03/2009	30/09/2009	30w 1d	Auto-cal procedure remained activated only for the polymer piezoelectric sensor system at the Landfill site (unknown reason)
8	**Static data conversion (Dec. 2008 to May 2009)**	16/03/2009	12/06/2009	13w	Converted static data of Dec. 08 to May 09 to the Excel format
9	**Prepared matching file: (Dec. 08 to May 09)**	01/04/2009	30/06/2009	13w	
10	**Preliminary Data analyses: (Jan. 2008 to May 2009)**	02/03/2009	31/12/2009	43w 4d	1- General analyses of data 2- Factorial Experiment Design and Analyses
11	**Continuous Data Supply**	01/10/2009	30/04/2010	30w 2d	Analysis of static weights of heavy trucks (Jan. to Sept. 2009) were finished
12	**Manual Re-calibration Using under developing CPATT's Manual Calibration Sheets**	03/05/2010	31/08/2010	17w 2d	1- All sensors were manually calibrated 2- An algorithm for manual calibration of MS-WIM system was developed 3- 50 km/hr, CPATT Dodge Sprinter van (approx. 3.0 tons), main wheel path (path run 2), 30 to 35 runs
13	**Continuous data supply**	01/09/2010	01/08/2011	47w 4d	
14	**Data analyses: (Jun. 2008 to Oct 2008)**	01/06/2011	01/08/2011	8w 4d	1- Frequency and Regression Analyses 2- Box and Cox Analyses

Figure 3-14- The Gantt chart for WIM activities at the Landfill site

ID	Tasks at the Highway 401 site	Start	Finish	Duration	2010						2011											
					Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	**The Highway 401 site:** **As-built, WIM system trouble-shoot,**	**04/10/2010**	**29/10/2010**	**4w**																		
2	**Pre-calibration settings for quartz and polymer piezoelectric sensors, for axle load, axle spacing and speed calibrations**	**15/10/2010**	**01/11/2010**	**2w 2d**																		
3	**Manual Calibration,** **Using CPATT's Manual Calibration Sheets**	**04/11/2010**	**04/11/2010**	**1d**																		
4	**Continuous data supply**	**05/11/2010**	**01/08/2011**	**38w 2d**																		

Figure 3-15- The Gantt chart for WIM activities at the Highway 401 site

Figure 3-16- A sample of garbage truck at the Landfill site

Figure 3-17- A sample of the Class 9 FHWA 5-axle truck

Figure 3-18- The CPATT van

At the Highway 401, only the main wheel path was selected and 100 km/hr speed for manual calibration for safety reasons.

3.1.3.4 Manual Calibration Results at the Landfill Site

The WIM sensors were manually calibrated using the CPATT van. Results of the calibration showed that polymer and ceramic piezoelectric sensor sets are susceptible to air temperature while the quartz sensors are insensitive to this factor (Figure 3-20). ASTM E 1318 defines performance requirements for class II WIM sensors as ±30%, ±20% and ±15% for axle, axle group and gross weights of vehicles respectively. For axle spacing and speed calibration, the sensors should operate within ±0.15 m and ±2 km/hr respectively. After manual calibration, the axle spacing measured by all sensors are in the acceptable range of ±1.5% (Figure 3-21), which is less than 15 cm.

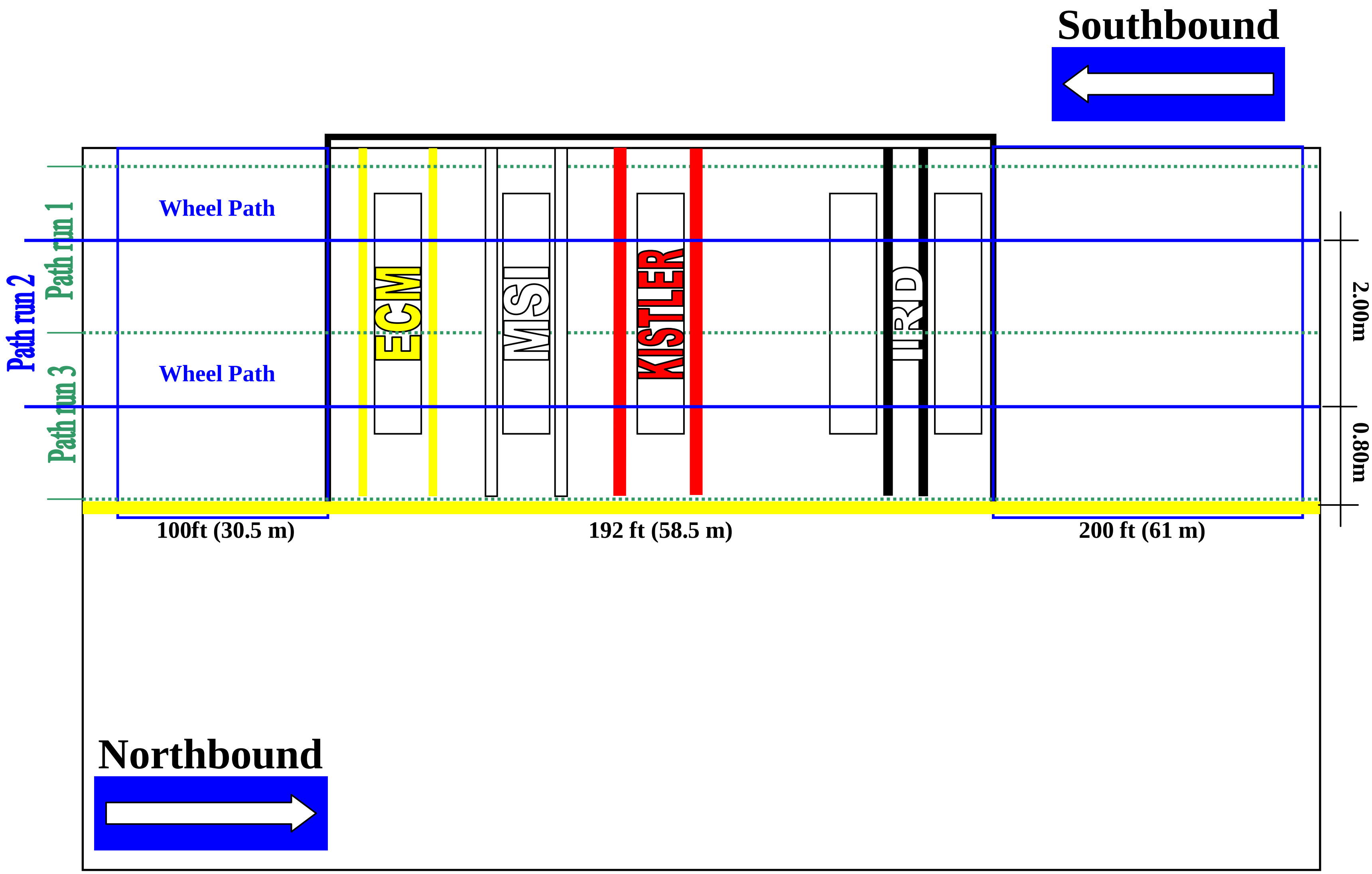


Figure 3-19- The location of sensors and path runs on the Lanfill site

3.1.3.5 Manual Calibration Results at the Highway 401 Site

At the Highway 401 site, the manual calibration sheets, developed, tested and improved by the author and were used for calibration of both quartz and the polymer piezoelectric sensors. The acceptable results for axle loads in this procedure are within the range of ±10%. The axle spacing calibration for the sensors at the highway 401 has not been performed yet; however, the estimation output of polymer piezoelectric sensors illustrated acceptable accuracies since the settings of the WIM system were checked and fixed precisely as a requirement for axle spacing calibration prior to axle weight calibration in November 2010. In order to be able to capture the effects of temperature, weight and speed factors the manual calibrations are performed every six months to a year.

3.1.3.6 Auto-Calibration Procedures at the Landfill Site

The auto-calibration was performed according to the supplier's instructions for at least 150 runs per day using the CPATT van, to ensure accurate and reliable data output from the polymer and ceramic piezoelectric sensors at the Landfill site. The experiments took several days each day consisted of between 125 and 185 runs over the sensors. The results showed improved accuracies of the sensors from ±10% to ±15% for polymer piezoelectric systems to ±20% for the ceramic piezoelectric, which means that in the vendor's auto-calibration algorithm there is a built in temperature correction (Figure 3-20 and Figure 3-21). However, the components of the algorithm are not accessible and cannot be customized according to the specific site characteristics.

Table 3-1 demonstrates the number of runs in the three categories of sensors estimation accuracies including less than 10%, 10% to 20% and more than 20%. Figure 3-22 illustrates that in three days of auto calibration using CPATT van with over 450 runs over the sensors there are visible improvements in sensors' accuracies. However, there is still room for improvement, and the auto-calibration approach is not well documented, tested or validated. This motivated further investigation.

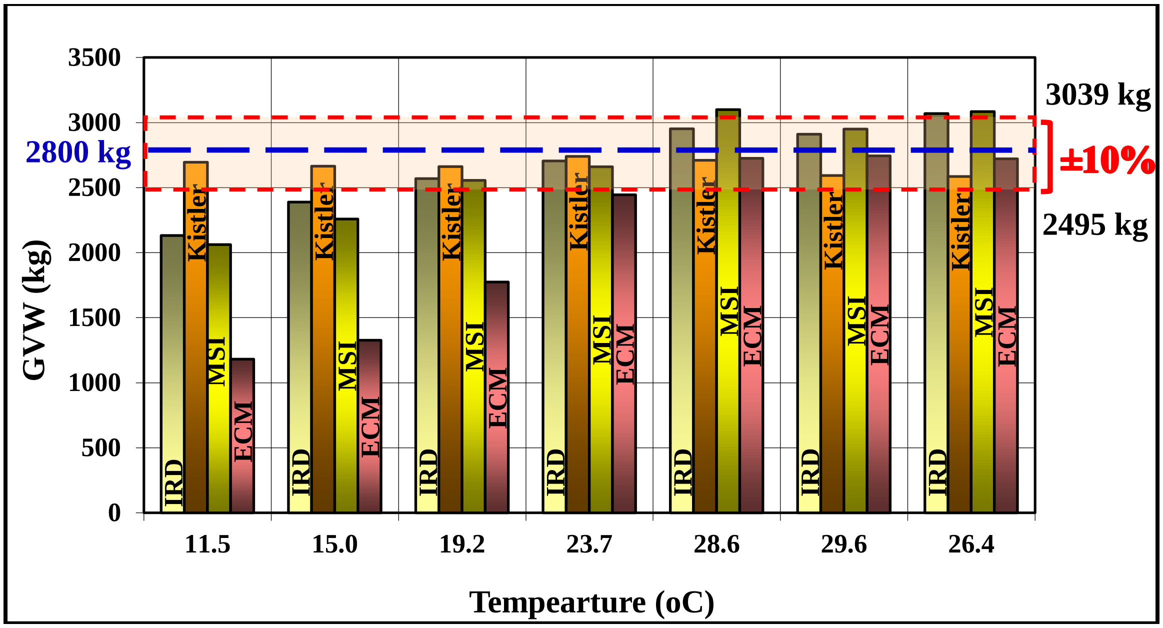


Figure 3-20- GVW of the van calculated by sensors during 28 May 2008

(The van's static GVW is 2800 kg and indicated by the dashed blue line)

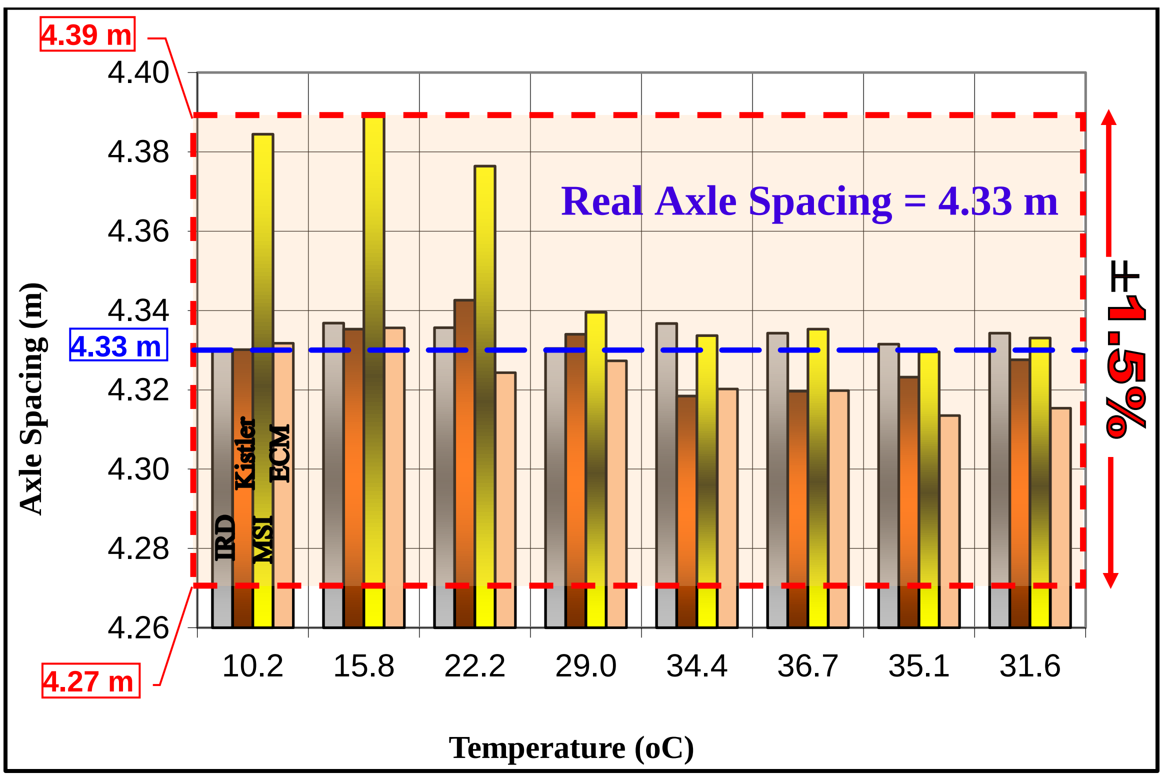


Figure 3-21- Axle spacing of the van calculated by WIM sensors during 28 May 2008

Table 3-1- Categorizing the percentages of runs in three fractions of accuracies with the van

Date	Sensor Type	< 10%		10%-20%		>20%	
		Runs	%	Runs	%	Runs	%
06-Jun-08 (126 Runs)	Polymer	83.0	65.9%	43	34.1%	0	0.0%
	Quartz	113.0	89.7%	13	10.3%	0	0.0%
	Polymer	82.0	65.1%	30	23.8%	14	11.1%
	Ceramic	71.0	56.3%	37	29.4%	18	14.3%
12-Jun-08 (150 Runs)	Polymer	112.0	74.7%	38	25.3%	0	0.0%
	Quartz	132.0	88.0%	18	12.0%	0	0.0%
	Polymer	145.0	96.7%	5	3.3%	0	0.0%
	Ceramic	69.0	74.2%	20	21.5%	4	4.3%
13-Jun-08 (185 Runs)	Polymer	156.0	84.3%	29	15.7%	0	0.0%
	Quartz	159.0	85.9%	26	14.1%	0	0.0%
	Polymer	179.0	96.8%	6	3.2%	0	0.0%
	Ceramic	141.0	76.2%	41	22.2%	3	1.6%

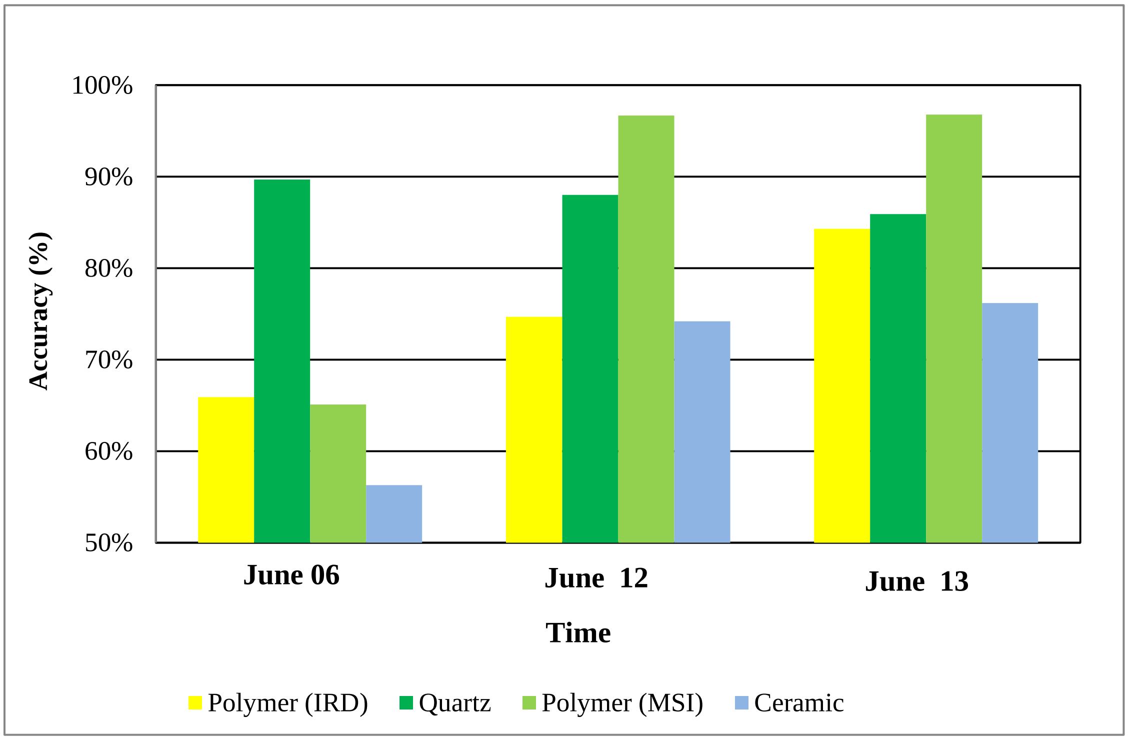


Figure 3-22- Improvements in the estimations of polymer and ceramic piezoelectric sensors

(**Three days of auto-calibration**)

3.2 Manual Calibration Sheets

A manual calibration procedure using the Microsoft Excel® program was developed as part of the research described in this thesis and improved and used for calibration of the sensor systems at the Landfill site in the summer 2010 specifically for quartz and polymer piezoelectric sensors.

The sheets were prepared mainly for calibration at the WIM sites. Therefore, the sheets were designed in a way that a user at a site can easily and quickly check the calibration status of WIM systems (Figure 3-23).

Unit	Veh.	LENG	Bum-1st	TODT	GVW	Drive Ax	2nd	3rd	4th	Gas	Air °C	Weather	Road		
SI	F150	5.9	0.6	3.7	2685.0	1530.0	1155.0								
		590.6	60.0	366.5	26.9	15.3	11.6								
US		1937.5	196.9	1202.5	59.2	33.7	25.5								
Trials	Sen.	1st	2nd	3rd	4th	5th	< 5%	F	New F	Finals		Date	Start	End	Air °C
1	P1							280		P1		Today()	17:00	17:15	
	P2							115		P2		Today()	17:00	17:15	
2	P1							280		P1		Today()	17:15	17:30	
	P2							115		P2		Today()	17:15	17:30	
								Decision		P1		Duration	0:30		
										P2					
3	P1							280		P1		Today()	17:30	17:45	
	P2							115		P2		Today()	17:30	17:45	
4	P1							280		P1		Today()	17:45		
	P2							115		P2		Today()	17:45		
								Decision		P1		Duration	0:15		
										P2					
								Final If Change is >10%		P1		Total	0:45		
										P2					
5	P1							280		P1		Today()			
	P2							115		P2		Today()			
6	P1							280		P1		Today()			
	P2							115		P2		Today()			
								Final Factors		P1		Duration	0:00		
										P2					
Final	P1									P1		Today()			
	P2									P2		Today()			

Figure 3-23- The Manual Calibration Sheet designed for the WIM sites

A WIM operator can start working with the sheets just by copying and pasting the traffic stream data from the WIM software to the sheets. The procedure will shortly calculate new calibration factors for the piezoelectric units (P1 and P2) if the calibration factor has significantly changed from current settings (Appendix D).

3.2.1.1 Calibration of Quartz and Polymer Piezoelectric Sensors at the Highway 401 Site

Due to temperature susceptibility, the polymer and ceramic piezoelectric WIM sensors should normally be operated under auto-calibration procedure, since the sensors are affected significantly by climate and traffic conditions at the site such as temperature, weight and speed of vehicles of which is a procedure, developed and provided by the vendor. The popular method requires that a pre-weighed vehicle travels repeatedly (more than hundred times) over the WIM site, which has the layout such as the highway 401 WIM site (Figure 3-24). The method can also use the normal traffic at the site to monitor the steering axle load and axle spacing in the drive tandem axle of class 9 trucks for weight and axle spacing calibration. This method requires that WIM operator have enough knowledge about their site traffic and climate characteristics.

In specific research targets such as this thesis, it was decided to operate the WIM sites under manual calibration for all sensor types in order to capture the patterns of sensors' susceptibilities to major factors affecting system's performance. In this situation, polymer and ceramic piezoelectric WIM sensors need to be manually recalibrated at specific time intervals such as six-month periods.

The quartz sensors have a different story. The quartz crystal sensing elements are naturally piezoelectric with negligible pyro-electric effect designed in a specific aluminum alloy structure. The quartz sensors have more stable data production under different conditions and do not require operating constantly under vendor's automatic calibration procedure. The vendors recommend using this process during initial calibration, e.g. for two to three days under natural traffic stream and where using a pre-weighed truck for calibration is not feasible. After initial adjustments of calibration factors, the automatic procedure is turned off for regular operations. Calibration efforts after that uses manual calibration process under the ASTM standard specifications for highway WIM systems (ASTM E 1318 2009). Calibration and recalibration of quartz sensors may be necessary less frequently than polymer or ceramic piezoelectric sensors.

The sensors' manufacturers recommend performing the calibration procedure sometime after installation because of the setting of the grouts. For instance, for quartz sensors, this period is recommended to be two weeks after installation. In addition, after some months, pavement deformation might happen. Regrinding would be necessary, if tires passing over the sensors made any unusual noises, or the sensors protruded more than 0.5 mm above the pavement. After regrinding, rechecking the calibration factors has been recommended by the vendor. The research team used the CPATT van (3 tons) for any tests or manual calibration of the sensors. A Thermistor string with nodes at 10 cm interval along the length of the string was installed at the gravel shoulder close to the WIM installation location and covered by 12 cm of asphalt. Therefore, two temperatures at the depth of the asphalt are available for WIM data analysis (Figure 3-25).

3.3 Matching data from the Static Scale and WIM Stations at the Landfill Site

An algorithm was developed to match the vehicles traveled between the static scale and WIM stations. The main procedure at the Waste Management Division at the region of Waterloo and the matching algorithm were explained in Appendix C. The reasons for matching between stations are explained as follows:

- Not all the trucks weighed at the scale travel over the WIM station. The trucks haul paper, plastic, aluminum can, etc. that will be recycled at the recycling plant (Figure C.1),
- Travel between two stations takes between 45 seconds to 2 minutes, depending mainly on the trucks speed, but also on rare queues, and
- Some trucks haul organic garbage to a place in between the scale and WIM station

A computer program was developed using Visual Basic 6®, which uses WIM data at the WIM site and static weights from the scale at the Waste Management facility at Erb. Street, Waterloo and matches the data using three main criteria as follows:

1- Type of garbage
2- Travel time between two stations (45” to 2 minutes)
3- The quartz sensor estimation error

The static weight files (prepared monthly in Adobe Acrobat® PDF format) had to be converted to the text format using a software named Able2Extract 5.0®. Files for the years 2008 and 2009 (until September 2009) were converted and statistically prepared for the matching program. Approximately 45% to 50% of the trucks weighed at static scale were matched with the trucks passed over the WIM site. The matched data for July to October 2008 used for this research thesis analyses, when the piezoelectric sensors were at their best structural and installation environment health conditions.

3.4 Static Scale Analysis of Weights for Heavy Trucks at the Landfill site

Statistical analysis of the heavy trucks at the Landfill site (classes 6 to 10) illustrate that there can be a maximum of five tons difference between the weights of unloaded trucks in different classes (Appendix C). Most of trucks at the Landfill site arrive fully loaded; however, this difference can be used to filter the fully loaded trucks from the light loaded trucks for data analyses in Chapter 4.

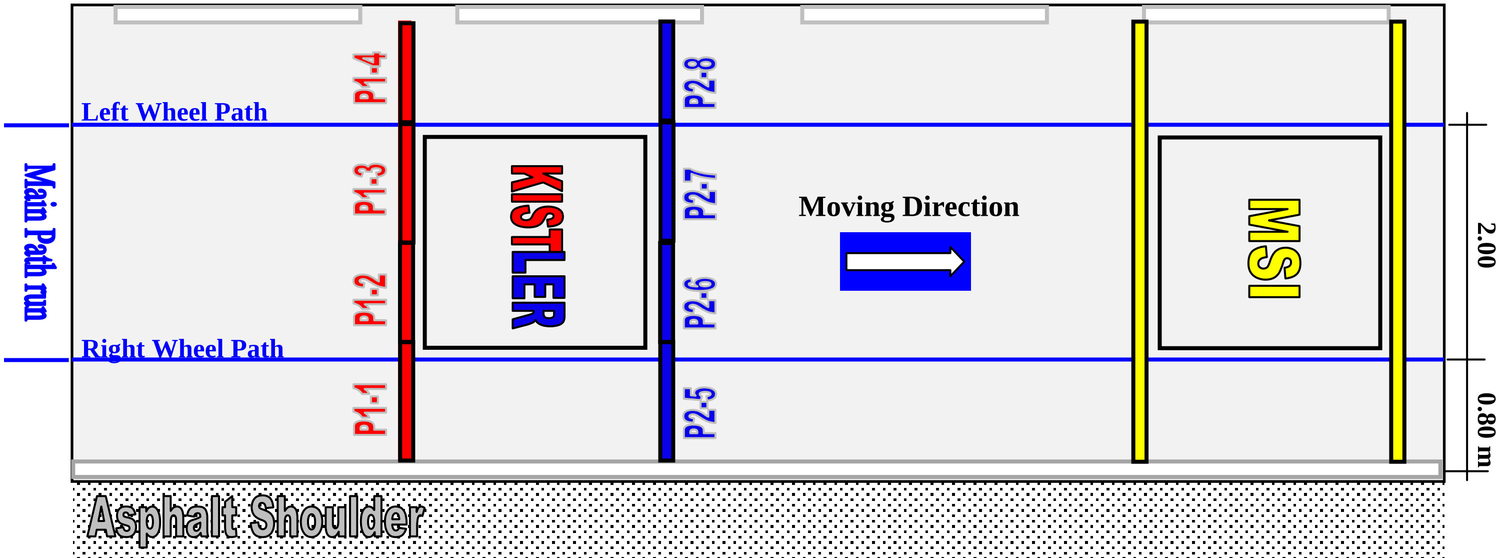


Figure 3-24- Layout of the quartz and polymer sensors at the Highway 401site

Figure 3-25- The installed Thermistor string covered by 12 cm asphalt

3.5 Piezoelectric WIM Sensor Raw Signal at the Landfill Site

After every installation, it is up to the user to collect the raw signal of the sensors or the corresponding axle weights generated by the system. This research study is based on the data generated by the ECM® Hestia® system at both CPATT experimental sites. However, there were some efforts to collect and investigate sensors' raw signals from the Landfill site in 2008, in order to learn how different piezoelectric sensor work and find an effective way to calibrate the sensors at the specific site.

3.5.1 The Quartz and Polymer Piezoelectric Sensors Output Signal at the Landfill Site

For a better understanding of the inherent behavior of the quartz sensor, a data acquisition system was introduced for raw signal collection. The chosen data logger has a cRIO-9014 as the embedded real-time controller. The data logger includes one digital input module and four A/D modules which can collect eight channels of digital input and sixteen channels of A/D channels. This meets the requirements for WIM information collection at the Landfill site. An Ethernet cable connects directly between computer and the data logger. The data acquisition software was developed using National Instrument (NI) Labview version 8.2.1 (National Instrument (NI) 2011). Figure 3-26 shows an example of the waveform collected from the quartz sensor for both strips of sensors, when a three-axle truck was passing the WIM. In this test, the data sampling rate was set to 1000 Hz. This figure shows that the quartz sensor has good performance when a dynamic pressure is applied on it, and that the approaching vehicle's pressure wave is isolated from the sensor's transducers effectively (Jiang et al. 2009).

The piezoelectric WIM sensors installed at the Landfill site have high insulation resistance (10^{10} Ω). Since the data logger's A/D module NI 9215 only has a 200 KΩ input resistance, when sampling a piezoelectric sensor, a charge amplifier is needed to convert a high insulation resistance sensor's electric charge signal to a low resistance voltage output signal. Figure 3-27 and Figure 3-28 illustrate output signals for the CPATT van at both average and less than average speeds, and Figure 3-29 illustrates output signals for a three-axle garbage truck at the Landfill site.

Figure 3-30 illustrates the signal outputs for polymer and quartz sensors at the Landfill site. Qualities of signals for two types of sensors are comparable. The polymer sensors show a higher deflection and a bigger negative signal caused by sensor's bending.

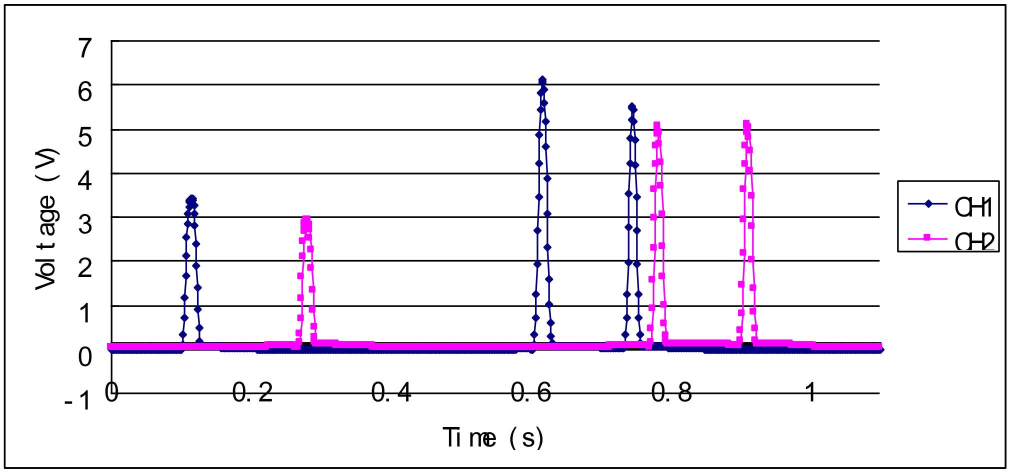


Figure 3-26- The quartz piezoelectric sensors' signal for a three-axle garbage truck

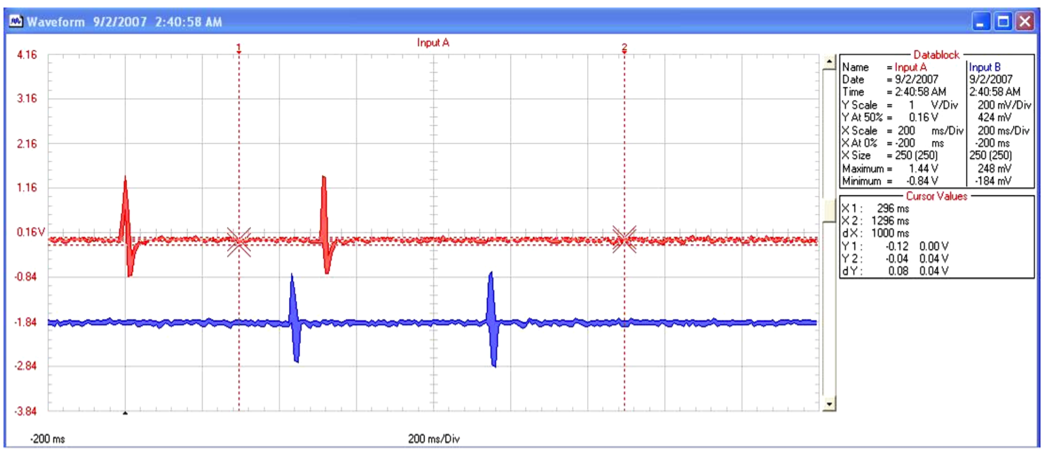


Figure 3-27- Polymer piezoelectric sensors signal for the CPATT van at 30 km/hr

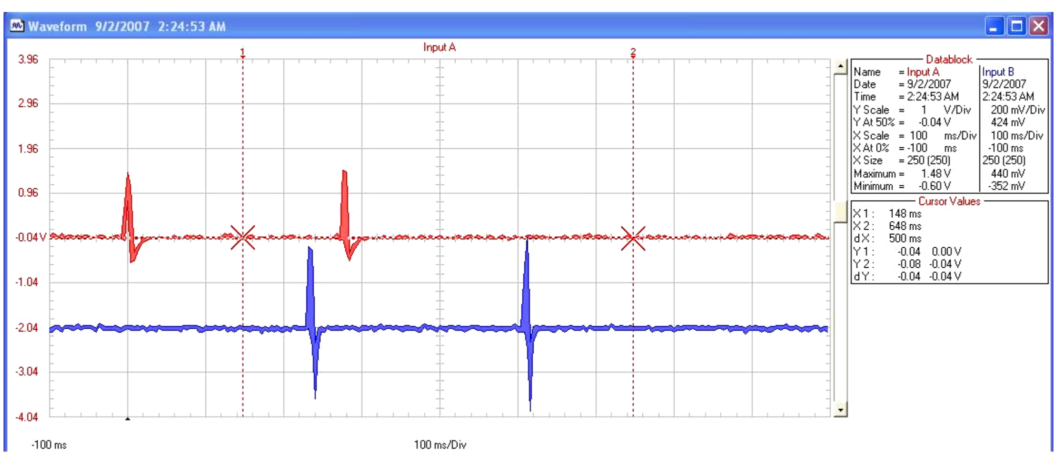


Figure 3-28- Polymer piezoelectric sensors signal for the CPATT van at 55 km/hr

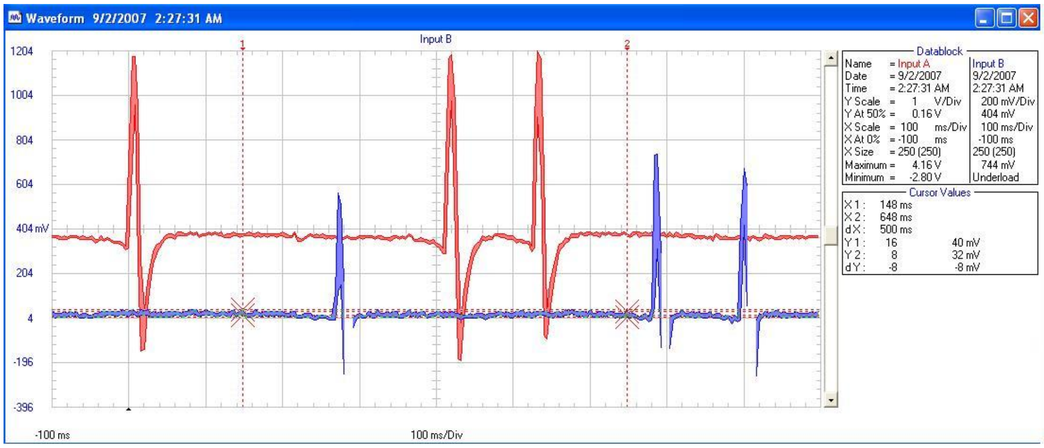


Figure 3-29- Polymer sensors (installed by IRD) signal for a three-axle garbage truck

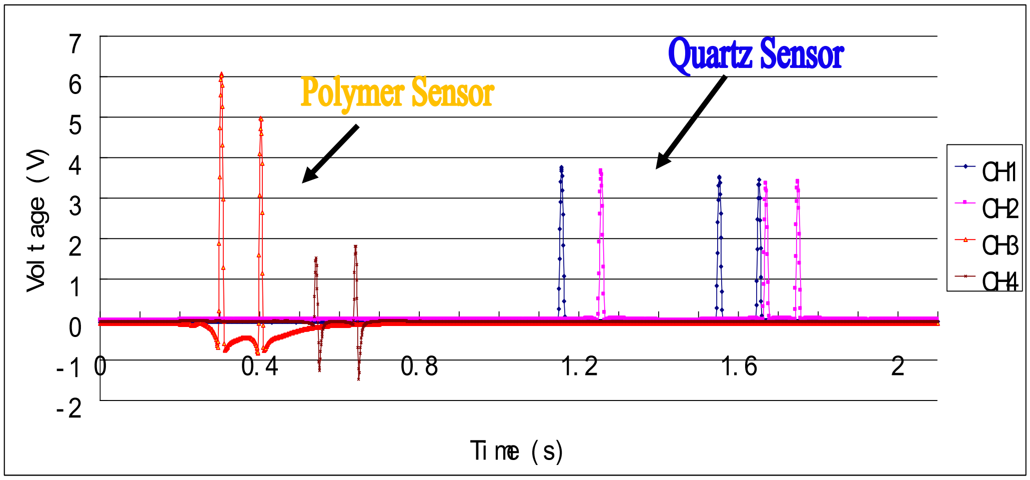


Figure 3-30- Polymer (IRD) and Quartz (Kistler) sensors' signal for a two-axle vehicle

Chapter 4
Weigh-In-Motion Data Analyses

4.1 Introduction

There are several factors, which may affect WIM sensors' accuracy such as path run, temperature, vehicle speed, etc., which cause piezoelectric WIM sensors to have different performances in different parts of the world with different climate patterns and road conditions. At the first set of analyses, the factorial experiment method was employed to investigate the effects of transverse location of axle load, air temperature (at warm and cold days) and speed on the sensors installed at the Landfill site using the CPATT Dodge Sprinter van. This study on the piezoelectric WIM sensors resulted in finding:

- The most influential factors,
- The effects of factors on the sensors, and
- Proper bin sizes for the factors, with which the factor will affect the sensors' estimations.

At the second round of analyses, the effect of weight, air temperature and speed factors were investigated on the piezoelectric WIM sensors at the Highway 401 site using traffic stream data. The effect of weight factor, which had not been studied in the first run of analyses, was analyzed using the Box and Cox method of transformation on the traffic stream data at the Landfill site, since static gross weights of vehicles passed over the WIM station were available at this site.

4.2 Piezoelectric WIM Sensors' Performance at the Landfill Site

To evaluate the performance of the WIM sensors, the significance of the effects of three factors including lane's path run, vehicle's speed and air temperature on each type of sensor were investigated using the factorial experiment method and data from the Landfill site. The design of the method (Montgomery, Runger 2003) is illustrated in Figure 4-1 (More details are in Appendix B). The impact of factors is indicated as very strongly, strongly, moderately, weakly and very weakly significant, which will be abbreviated as VSS, SS, MOS, WS and VWS respectively. There are some points to be considered in the experiments as follow:

1. In every experiment, only two factors at a time are tested. For instance, to test the sensitivity of the sensors to path run and temperature factors, the test vehicle was driven over different path runs on the southbound lane with the same speed, e.g. 50 km/hr during the test day. The path runs illustrated in Figure 3-19, include path runs 1, 2 and 3, which are explained as close to the right shoulder, on the middle and close to the yellow line on the left side of the lane respectively;

2. The horizontal dotted lines in some of the plots for investigating the interaction factor between factors present the static weight of the CPATT test van. The illustrated points in these graphs are the averages of “n” replicates at those points;
3. The polymer sensors were surprisingly shown insensitive to the air temperature factor in the CPATT experiments during March 2009. The suspicious sensors were found to be working under auto-calibration despite computer commands made to the contrary. However, this option was unchecked (meaning turned on) in the system from October 2008 to September 2009 only for the polymer sensors and other sensors worked under manual calibration over that period. The vendor explained that for an unknown reason, the auto-cal option for the sensors cannot be constantly turned off by just un-checking the auto-cal activation checkbox in the WIM software. The issue was fixed by removing all auto-calibration adjustments from the system in September 2009. Therefore, from the last auto-calibration turn off in October 01, 2008 the system was working under the auto-cal setting for the polymer sensors on March 2009. Schedules of calibration and data supply for both sites are displayed in Figure 4-2;
4. The normality assumption and presence of any outlier were checked to prove whether the residuals were normally and independently distributed NID (0, σ^2) with mean zero and constant but unknown variance, using normal probability plotting (NPP) and the standardized residuals (SR). Equation 2 (Rawlings, Pantula & Dickey 1998) standardizes the residuals (e_{ijk}) by dividing them by the mean square error (MSE), which is computed in the analysis of variance (ANOVA) table prepared for the sensors. The SRs’ absolute values should not exceed (+3) for normal distributions (Montgomery 2001).

$$Standardized\ Residual\ (SR) = \frac{e_{ijk}}{\sqrt{MSE}}$$

Equation 2- Standardized Residual

The results of this stage is also used to specify optimum factors’ level sizes requires for developing an auto-compensation algorithm for the WIM sensors in future phases of research. More details are in Appendix B.

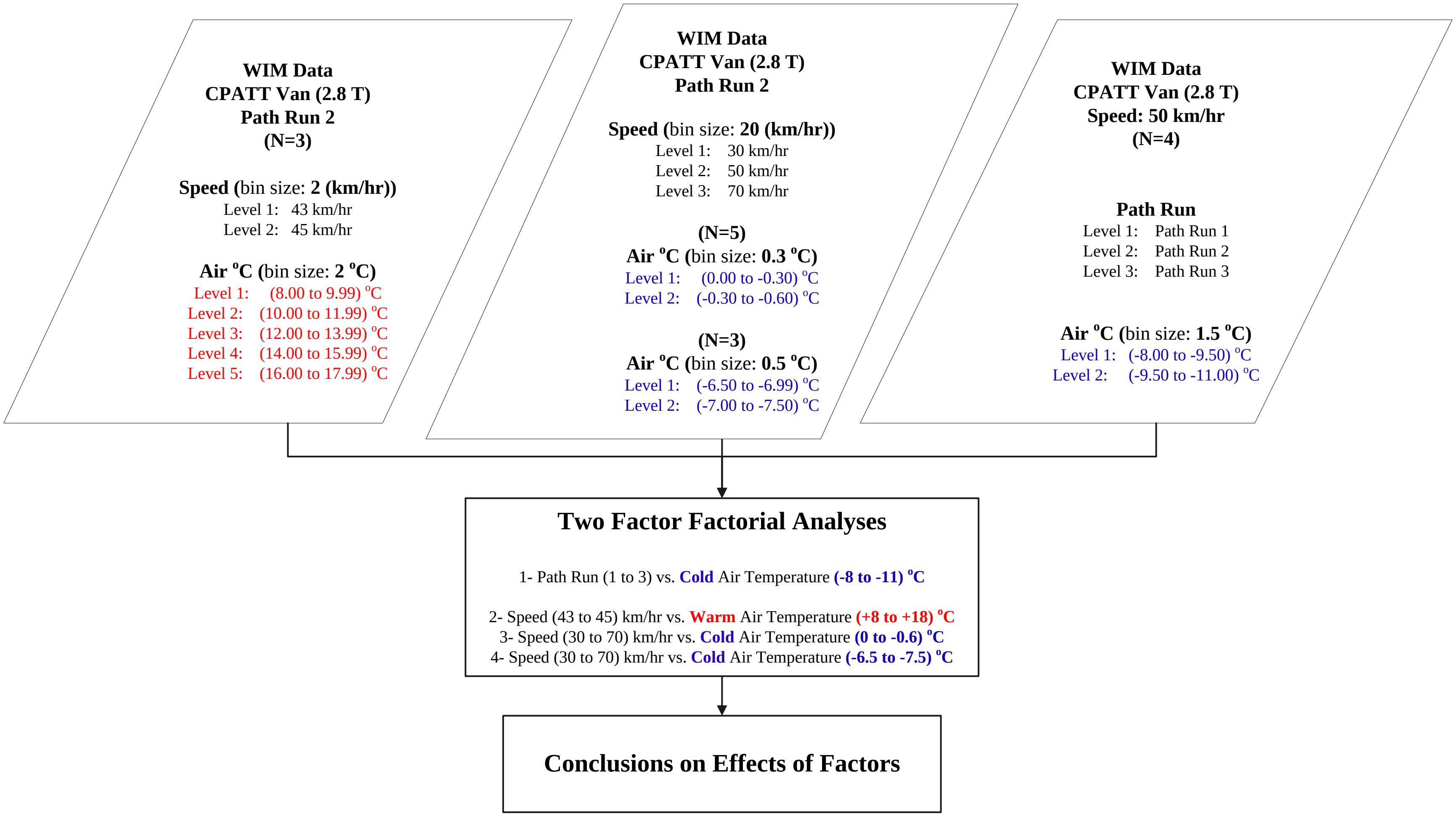


Figure 4-1- Design of the factorial experiment

ID	Manual and Vendor's Auto-calibration Tasks at the CPATT Experimental Sites	Start	Finish	Duration	Task Notes
1	**The Landfill Site: Manual Pre-calibration, Spotty limited data supply**	01/01/2008	30/04/2008	17w 2d	A few waveform recordings
2	**Manual calibration : Interrupted data supply**	01/05/2008	30/05/2008	4w 2d	
3	**Auto-calibration (ceramic and polymer piezoelectric sensors): Continuous data supply**	02/06/2008	30/09/2008	17w 2d	Request for static weight data from Waste Management, (Jan. 2008 to the end of May 2009)
4	**Auto-cal procedure deactivated: Continuous Data Supply**	01/10/2008	25/09/2009	51w 3d	Auto-cal procedure remained activated only for the polymer piezoelectric sensor system at the Landfill site (unknown reason)
5	**Manual Re-calibration**	04/03/2009	04/03/2009	1d	Auto-cal procedure remained activated only for the polymer piezoelectric sensor system at the Landfill site (unknown reason)
6	**Continuous Data Supply**	05/03/2009	30/09/2009	30w	Auto-cal procedure remained activated only for the polymer piezoelectric sensor system at the Landfill site (unknown reason)
7	**Vendor's auto-cal procedure on polymer piezoelectric sensors was deactivated: Continuous Data Supply**	01/10/2009	30/04/2010	30w 2d	All sensor sytems at the Landfill site started working under manual calibration factors
8	**Manual Re-calibration Using under developing CPATT's Manual Calibration Sheets**	03/05/2010	31/08/2010	17w 2d	1- All sensors were manually calibrated 2- An algorithm for manual calibration of MS-WIM system was developed 3- 50 km/hr, CPATT Dodge Sprinter van (approx. 3.0 tons), main wheel path (path run 2), 30 to 35 runs
9	**Continuous data supply**	01/09/2010	01/08/2011	47w 4d	
10	**The Highway 401 site: Pre-calibration settings for quartz and polymer piezoelectric sensors, for axle load, axle spacing and speed calibrations**	15/10/2010	01/11/2010	2w 2d	1- Frequency and Regression Analyses 2- Box and Cox Analyses
11	**Manual Calibation**	04/11/2010	04/11/2010	1d	This task used the improved CPATT's Manual Calibration Sheets
12	**Continuous data supply**	05/11/2010	01/08/2011	38w 2d	Data on November 2010, March 2011 and April 2011 are available

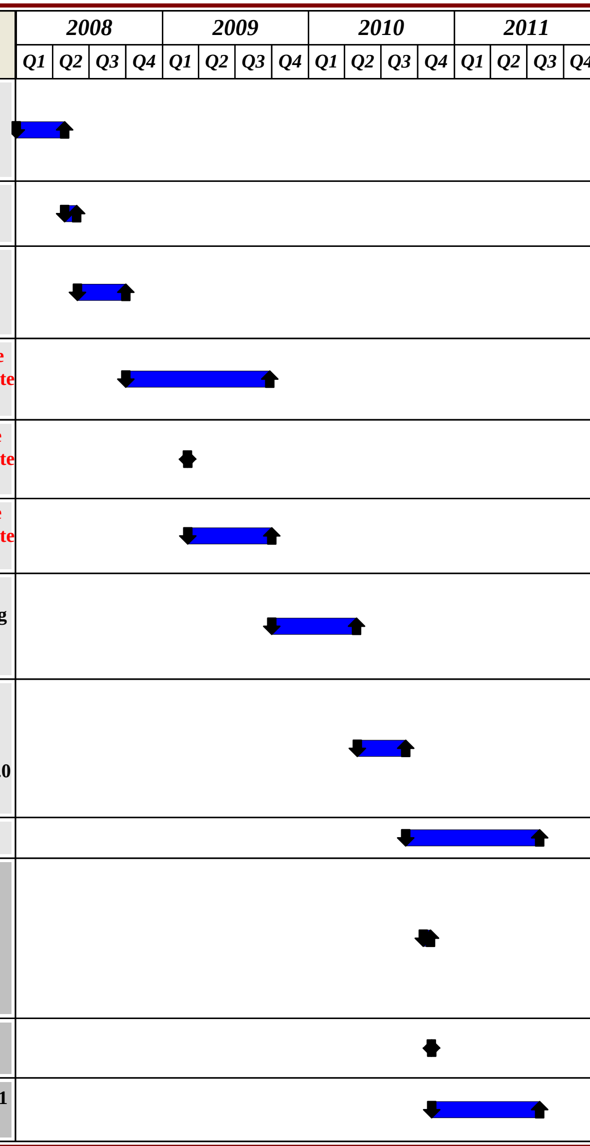


Figure 4-2-Calibration and supply of data schedules at the Landfill and Highway 401 sites

4.2.1 The Effect of Air Temperature on Performance of the WIM Sensors

On May 28, 2008 the first experiment performed to evaluate the effect of air temperature on the WIM sensors' output. This time of the year selected since the air temperature can vary from less than +10^{o}C to approximately +20 ^{o}C. The CPATT van was used to travel at 50 km/hr over path run 2. Table 4-1 presents the averages of GVW estimations in different air temperatures during the test day and the percent difference between the average values and the static weight of the test vehicle for each sensor type.

The visual relationships between air temperature and WIM sensors' outputs in Figure 4-3 reveal that quartz sensors are insensitive to temperature effect while the polymer and ceramic sensors show susceptibility to this factor. According to the visual trends in Figure 4-3 and GVW estimations in Table 4-1, the polymer and ceramic sensors show estimations with approximately ±15% difference with the static GVW of the test vehicle, when air temperature is in the range of 12 ^{o}C to 17 ^{o}C. The possible reason is that at the last WIM system calibration the air temperature was in this amplitude.

To evaluate the effect of temperature on WIM sensors, the data on May 28, 2008 were used to design a two-factor factorial fixed-effects model including temperature and speed with three replicates. The factors presented in five air temperature levels, included (8.00 to 9.99), (10.00 to 11.99), (12.00 to 13.99), (14.00 to 15.99), and (16.00 to 17.99) degrees of Celsius, and two speed levels, included 43 and 45 km/h, according to the WIM system speed estimations and the speed limit at the landfill site.

4.2.1.1 The Quartz Sensor

The quartz sensors' data arrangements are demonstrated in Table B. 1 (Appendix B) and the analysis of variance for this sensor are summarized in Table 4-2. The computations show that temperature and speed have no significant effect on the performance of this sensor considering the levels of factors specified for this analysis. The graph for means of estimated GVW versus temperature for each speed level (Figure 4-4) illustrates negligible interaction since the lines in both graphs are nearly parallel. A normal probability plot (NPP) of the residuals (Figure 4-5) illustrates no severe deviations from normality. The standardized residual computations resulted also in the values that lie in (-3) to (+3) interval which means that all residuals are in the range of a normal distribution including no outlier.

In conclusion, the quartz sensors' weight estimations seem to be insensitive to temperature and speed effects considering the levels and their sizes specified for the factors in this experiment.

Table 4-1– Air temperature effects on WIM sensors' GVW estimation at the Landfill site, May 28, 2008

Air (°C)	Quartz (kg)	Error (%)	Polymer (kg)	Error (%)	Ceramic (kg)	Error (%)
+9	2637.3	-5.1%	2005.5	-27.9%	1156.7	-58.4%
+10	2567.3	-7.6%	2340.5	-15.8%	1206.6	-56.6%
+11	2620.2	-5.7%	2668.2	-4.0%	1729.0	-37.8%
+12	2721.6	-2.1%	2712.5	-2.4%	2340.5	-15.8%
+13	2653.5	-4.5%	3007.3	8.2%	2689.8	-3.2%
+14	2562.8	-7.8%	2925.7	5.2%	2835.0	2.0%
+15	2600.6	-6.5%	3245.7	16.8%	2923.2	5.1%
+16	2671.7	-3.9%	3179.7	14.4%	3223.5	16.0%
+17	2627.1	-5.5%	2974.8	7.0%	3010.7	8.3%

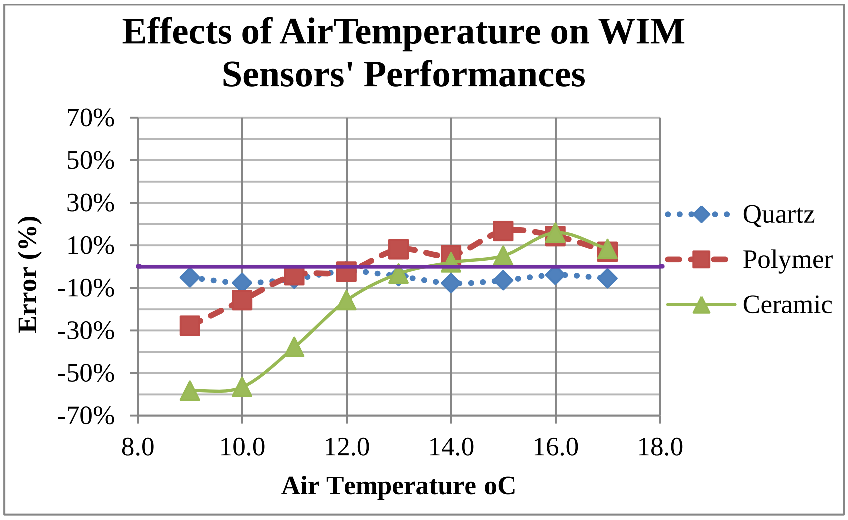


Figure 4-3– The effect of air temperature on piezoelectric WIM sensors

Table 4-2– ANOVA table for air temperature and speed effects on the quartz sensors

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	P-Value	Significance
Air Temperature (A)	75851.7	4	18962.9	1.78	0.1<P<0.25	VWS
Speed (B)	5555.1	1	5555.1	0.52	>0.25	
Interaction (AB)	13304.9	4	3326.2	0.31	>0.25	
Error	212604.2	20	10630.2			
Total	307316.0	29				

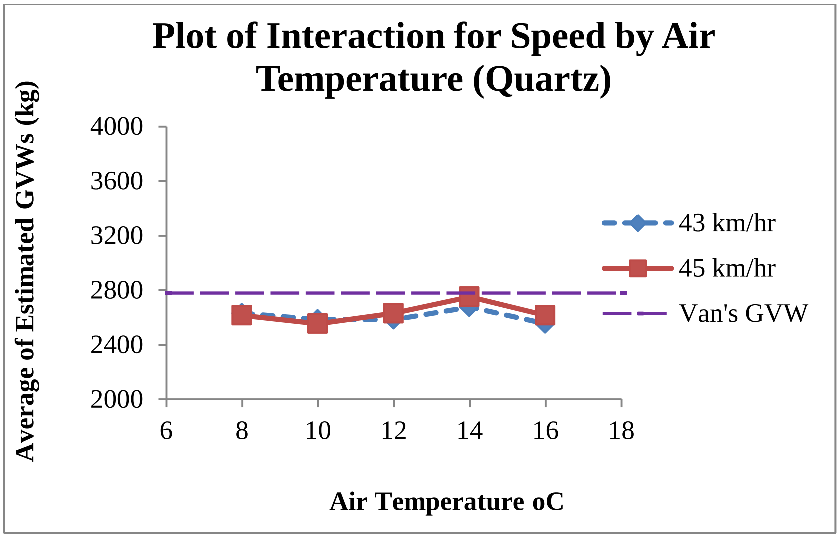


Figure 4-4– The interaction effect for speed by air temperature in the temperature experiment (quartz)

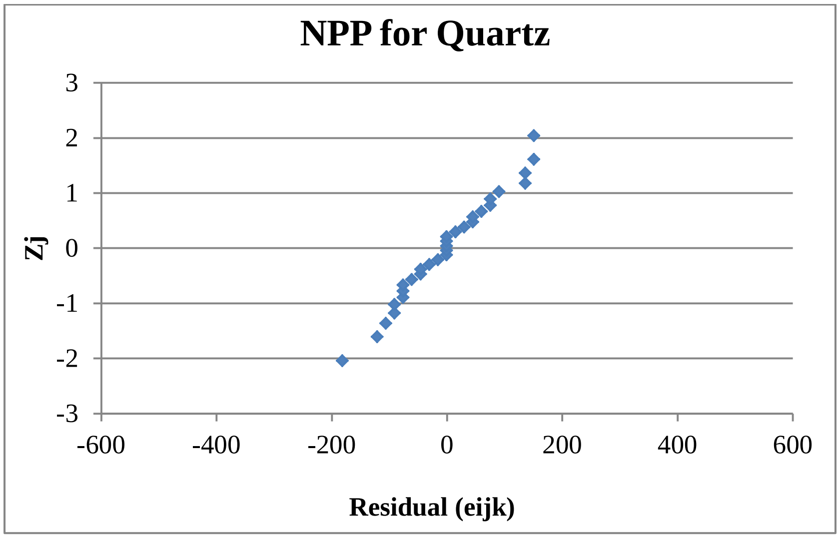


Figure 4-5– Plot of the quartz residuals for the temperature and speed experiment

4.2.1.2 The Polymer Sensor

The polymer sensors' data arrangements are displayed in Table B. 2 (Appendix B) and the analysis of variance for this sensor summarized in Table 4-3. The computations show that temperature has significant effect on the performance of this sensor considering 2^{o}C level size specified for the temperature factor. The graphs of means of estimated gross vehicle weight (GVW) versus speed for each temperature level (Figure 4-6) and means of estimated GVW versus temperature for each speed (Figure 4-7) illustrate a direct relationship between air temperature and the sensors' means of estimated GVWs including negligible interaction between the factors. A normal probability plot of the residuals (Figure 4-8) and standardized residual computations demonstrate no severe deviations from normality including no outlier.

In conclusion, the polymer sensors' estimations seem to be sensitive to temperature and insensitive to the speed effects considering the factors' levels and their sizes in this experiment.

Table 4-3– ANOVA table for air temperature and speed effects on the polymer sensors

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	P-Value	Significance
Air Temperature (A)	4099421.2	4	1024855.3	36.54	<<0.01	**VSS**
Speed (B)	17557.0	1	17557.0	0.63	>0.25	
Interaction (AB)	77772.0	4	19443.0	0.69	>0.25	
Error	561000.9	20	28050.0			
Total	4755751.1	29				

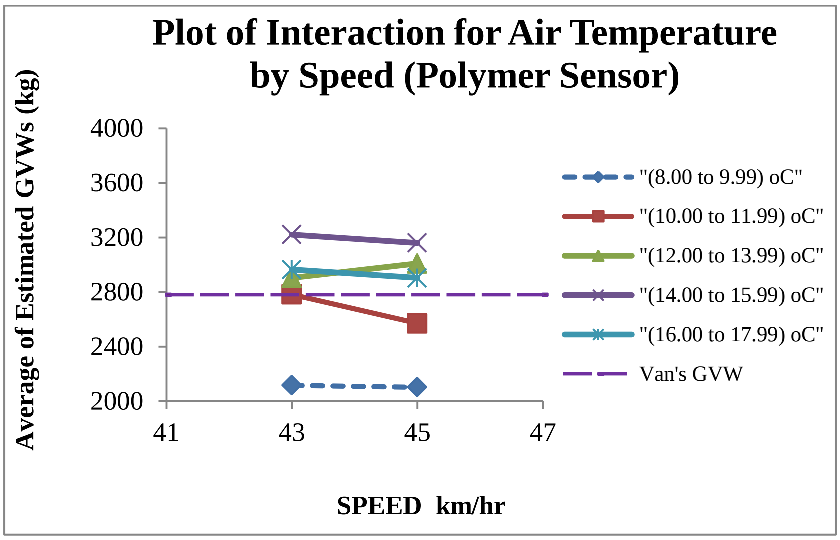


Figure 4-6– The interaction effect for air temperature by speed in the temperature experiment (polymer)

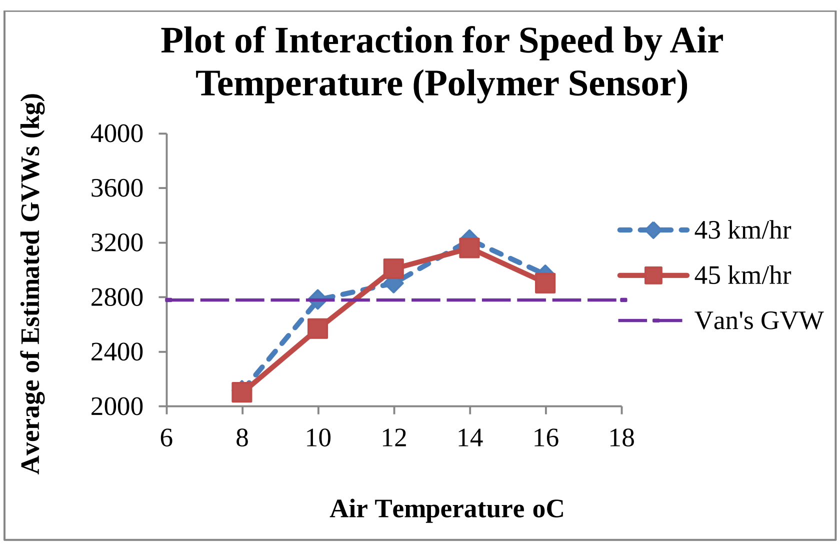


Figure 4-7– The interaction effect for speed by air temperature in the temperature experiment (polymer)

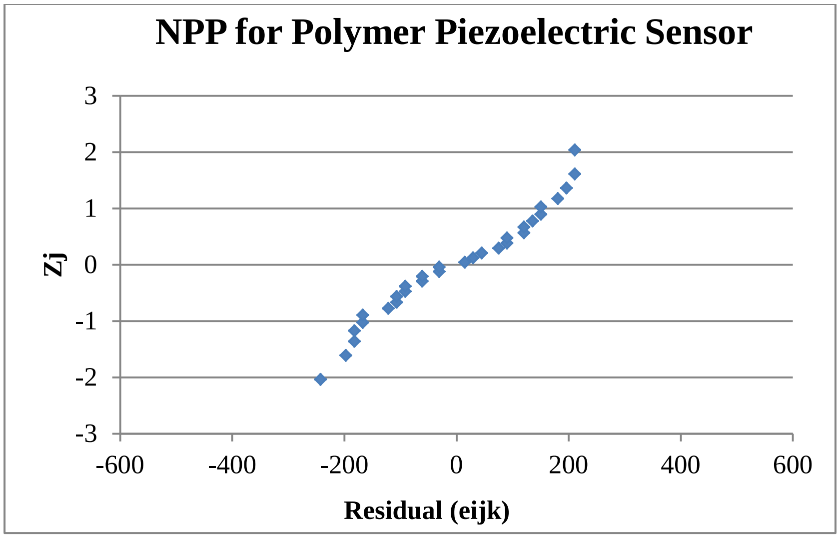


Figure 4-8– Plot of the polymer residuals for the temperature and speed experiment

4.2.1.3 The Ceramic Sensor

The ceramic sensors' data arrangements are displayed in Table B. 3 (Appendix B) and the analysis of variance for this sensor summarized in Table 4-4. The computations show that temperature has significant effect on the performance of this sensor considering 2^{o}C level size specified for air temperature. The means of estimated van's GVW versus speed for each temperature level (Figure 4-9) illustrate a direct relationship between air temperature and the sensors' means of estimated GVWs including negligible interaction between factors. A normal probability plot of the residuals (Figure 4-10) and standardized residual computations demonstrate no severe deviations from normality including no outlier, which mean that all residuals are in the range of a normal distribution. In conclusion, the ceramic sensors' weight estimations seem to be sensitive to temperature and insensitive to the speed effect considering the factors' levels and their sizes in this experiment.

Table 4-4– ANOVA table for air temperature and speed effects on the ceramic sensors

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F_0**	**P-Value**	**Significance**
Air Temperature (A)	18347334.4	4	4586833.6	80.97	<<0.01	**VSS**
Speed (B)	68.6	1	68.6	0.00	>0.25	
Interaction (AB)	45538.5	4	11384.6	0.20	>0.25	
Error	1132974.8	20	56648.7			
Total	19525916.3	29				

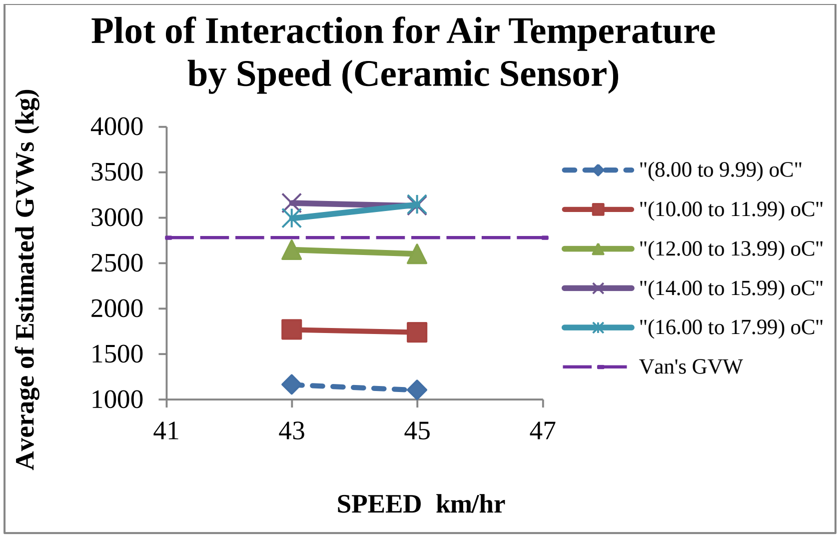


Figure 4-9– The interaction effect for air temperature by speed in the temperature experiment (ceramic)

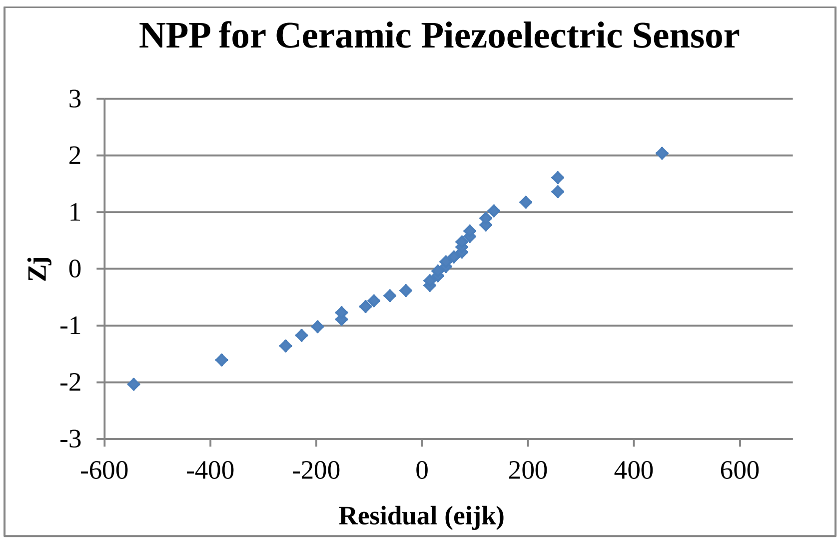


Figure 4-10– Plot of the ceramic residuals for the temperature and speed experiment

4.2.2 The Effect of Transverse Location of Axle Loads on the Sensors' Performance

On March 03, 2009, the second set of tests were carried out using the CPATT van with the speed 50 km/hr over three path runs and in two temperature levels (Hashemi Vaziri et al. 2012). The data was used to test a two-factor factorial fixed-effects model including four replicates. The following sections present WIM data arrangements and analysis of variance per sensor type and conclude according to the results of this analysis.

4.2.2.1 The Quartz Sensor

The quartz sensors data arrangements demonstrated in Table B. 4 (Appendix B). The analysis of variance computations (Table B. 5) show that the path run has significant effect on the quartz sensors since the results on path run 1 are significantly different from other path runs. The possible reason for this is that the tire loads were not fully on the sensors in path run 1. Figure 4-11 illustrates no-interaction since the lines are nearly parallel; however, the line for speed 30 km/hr show a significant different estimation. A normal probability plot of the residuals (Figure B. 1) and standardized residual computations demonstrated that all residuals are in the range of a normal distribution including no outlier.

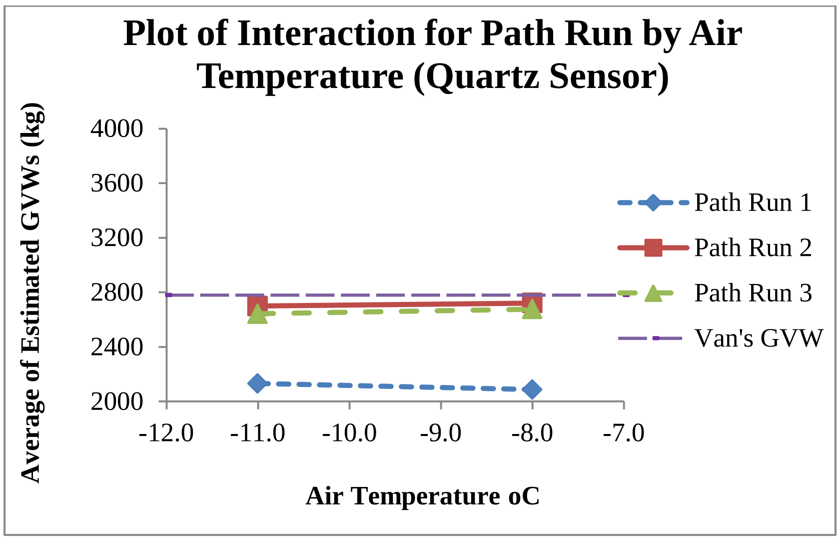


Figure 4-11– The interaction effect for path run by air temperature (quartz)

4.2.2.2 The Polymer Sensor

The polymer sensors data arrangements demonstrated in Table B. 6 (Appendix B). The analysis of variance computations (Table B. 7) and the crossed lines in Figure 4-12 and Figure 4-13 illustrate a significant interaction between the path run and the air temperature factors. The possible reason is the sensitivity of the polymer sensors to both path run and air temperature, which is more related to significantly different estimations over path run 2. However, it is noticeable that the absolute values of the percent differences between estimated GVWs and the static weight of the test vehicle are just between 7 to 11 percent, since the polymer sensors were found to have been working under the auto-cal process. A normal probability plot of the residuals (Figure B. 2) and standardized residual computations demonstrated that all residuals are in the range of a normal distribution including no outlier.

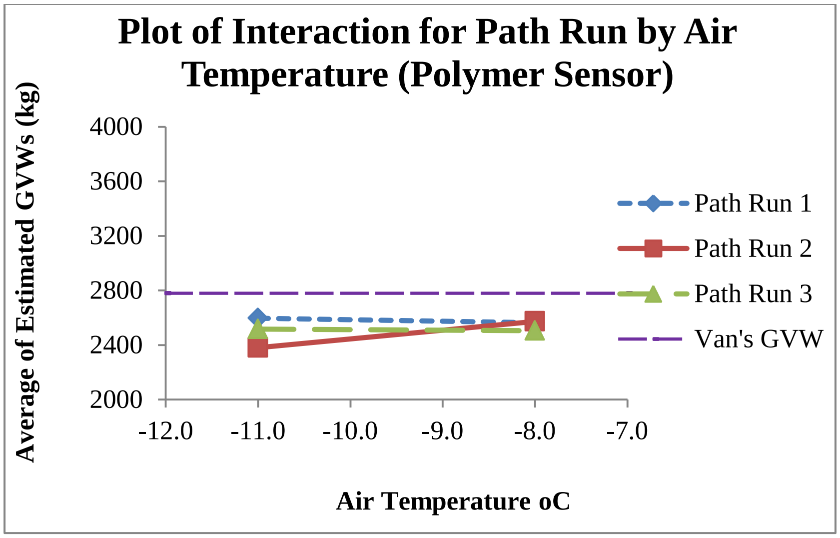


Figure 4-12– The interaction effect for path run by air temperature (polymer)

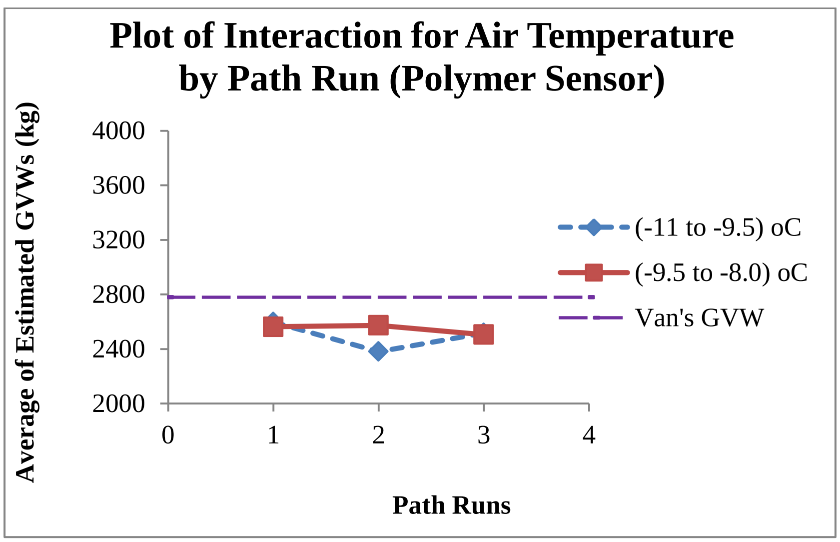


Figure 4-13– The interaction effect for air temperature by path run (polymer)

4.2.2.3 The Ceramic Sensor

The ceramic sensors' data arrangements demonstrated in Table B. 8 (Appendix B). The analysis of variance computations (Table B. 9) and the crossed lines in Figure 4-14 and Figure 4-15 illustrate a significant interaction between path run and temperature. It seems that the sensor overestimated the weights on path run 2. The reasons can be possibly described by the ceramic sensors' need to be recalibrated to eliminate the effect of temperature and explained by the sensor's edge effect. A normal probability plot of the residuals (Figure B. 3) and standardized residual computations demonstrated that all residuals are in the range of a normal distribution including no outlier.

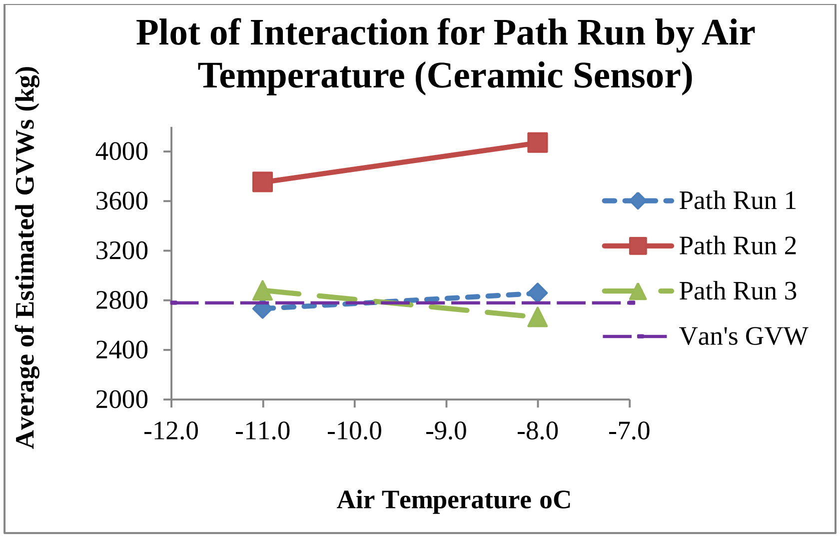


Figure 4-14– The interaction effect for path run by air temperature (ceramic)

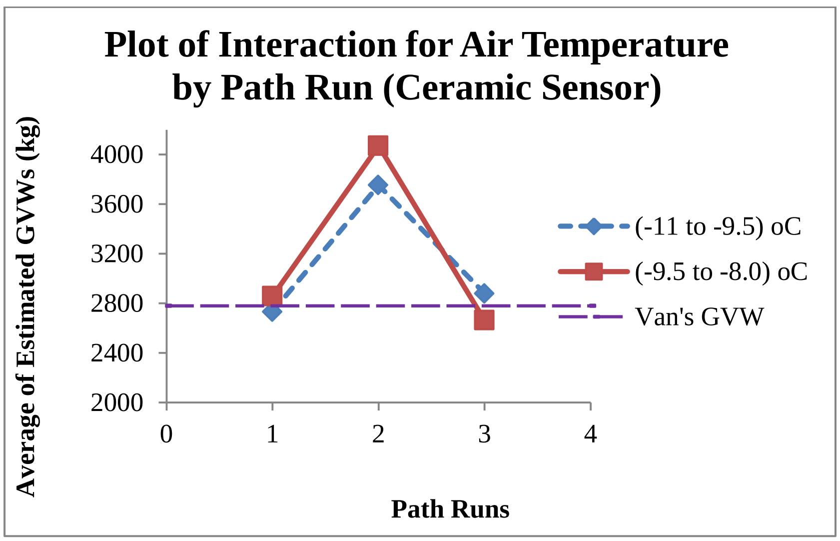


Figure 4-15– The interaction effect for air temperature by path run (ceramic)

4.2.3 The Effect of Vehicle Speed on Performance of the WIM Sensors

The third experiment on March 03, 2009 performed using the CPATT Sprinter van in three speeds and two temperature levels. The resulted WIM data utilized to design a two-factor factorial fixed-effects model including three replicates. The following sections present WIM data arrangements and analysis of variance per sensor type and conclude according to the results of this analysis.

4.2.3.1 The Quartz Sensor

The quartz sensors' data arrangements are displayed in Table B. 10 (Appendix B). The analysis of variance computations (Table B. 11) and the approximately parallel lines in Figure 4-16 illustrate negligible interaction between speed and temperature. It seems the GVW estimations in speeds more than 50 km/hr are more consistent and closer to the van's static GVW than other speeds. The possible reason can be either the sensors' need to be recalibrated or sensitivity of the quartz sensors to the speeds lower than 30 km/hr. A normal probability plot of the residuals (Figure B. 4) and standardized residual computations demonstrated that all residuals are in the range of a normal distribution including no outlier.

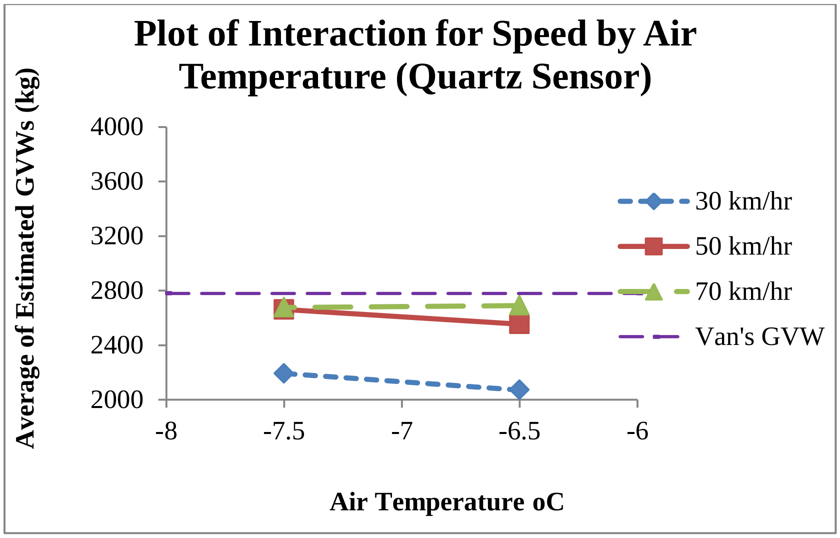


Figure 4-16– The interaction effect for speed by air temperature (quartz)

4.2.3.2 The Polymer Sensor

The polymer sensors' data arrangements are displayed in Table B. 12 (Appendix B). The analysis of variance computations (Table B. 13) and the lines in Figure 4-17 illustrate that speed has significant effect on the sensors specifically for speeds lower than 30 km/hr including negligible interaction. The possible reason can be either the sensors' need to be recalibrated or sensitivity of the sensors to speeds less than 30 km/hr. A normal probability plot of the residuals (Figure B. 5) and standardized residual computations showed that all residuals are in the range of a normal distribution including no outlier.

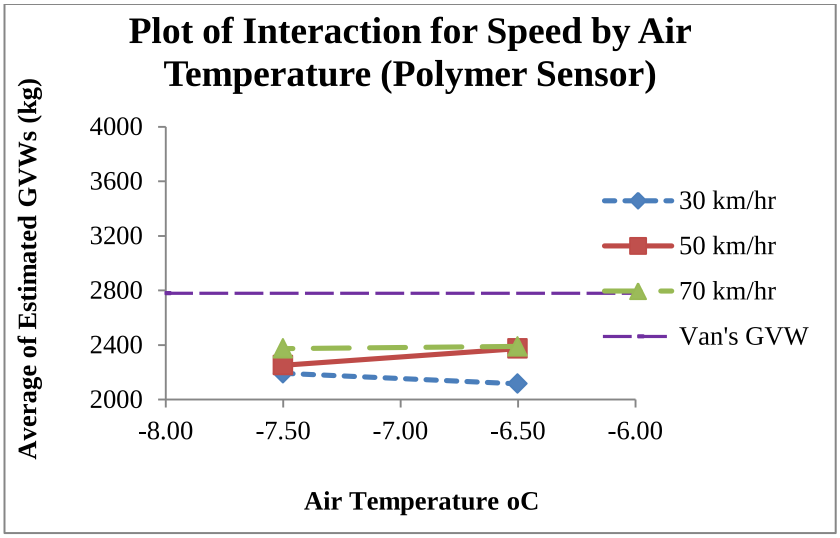


Figure 4-17– The interaction effect for speed by air temperature (polymer)

4.2.3.3 The Ceramic Sensor

The ceramic sensors' data arrangements demonstrated in Table B. 14 (Appendix B). The analysis of variance computations (Table B. 15) and the lines in Figure 4-18 and Figure 4-19 show that speed has significant effect on the ceramic sensors including a week interaction between speed and temperature in lower speeds (30km/hr) and no interaction in higher. It seems that the sensors overestimate the weights in higher speeds (50 and 70 km/hr). The reasons can be possibly described by the ceramic sensors' need to be recalibrated. A normal probability plot of the residuals (Figure B. 6) and standardized residual computations demonstrated that all residuals are in the range of a normal distribution including no outlier.

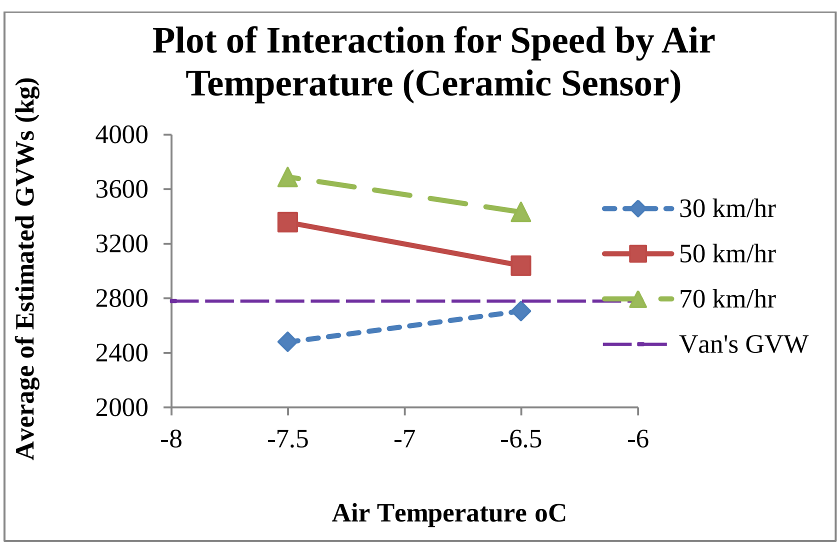


Figure 4-18– The interaction effect for speed by air temperature (ceramic)

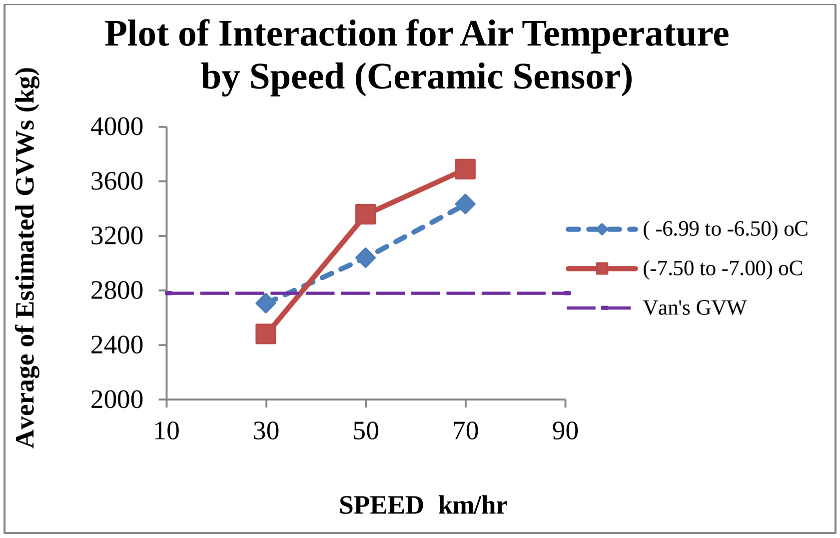


Figure 4-19– The interaction effect for air temperature by speed (ceramic)

4.2.4 The Effect of Vehicle Speed on Performance of the Newly Calibrated Sensors

On March 04, 2009 the fourth and last set of experiments were carried out after recalibration of the sensors, which took place in the morning. This experiment was performed using the CPATT van at three speeds and two temperature levels, to compare with the result of the same experiment on March 03, 2009. The WIM data utilized to experiment a two-factor factorial fixed-effects model including five replicates. The following sections present WIM data arrangements and analysis of variance per sensor type and conclude according to the results of this analysis.

4.2.4.1 The Quartz Sensor

The quartz sensors' data arrangements are displayed in Table B. 16 (Appendix B). The analysis of variance computations (Table B. 17) show and the lines in Figure 4-20 illustrate that the effect of speed has changed to moderately significant since the sensors' estimations at speeds lower than 30 km/hr are still different from estimations at higher speeds including negligible interaction between factors. A normal probability plot of the residuals (Figure B. 7) and standardized residual computations showed that all residuals are in the range of a normal distribution including no outlier. In conclusion, the quartz sensors' weight estimations seem to be insensitive to temperature effect during the test period. The weight estimations are also more consistent and closer to the van's static GVW in speeds 50 to 70 km/hr. According to the results of this study, at least one recalibration per year is recommended for the quartz sensors.

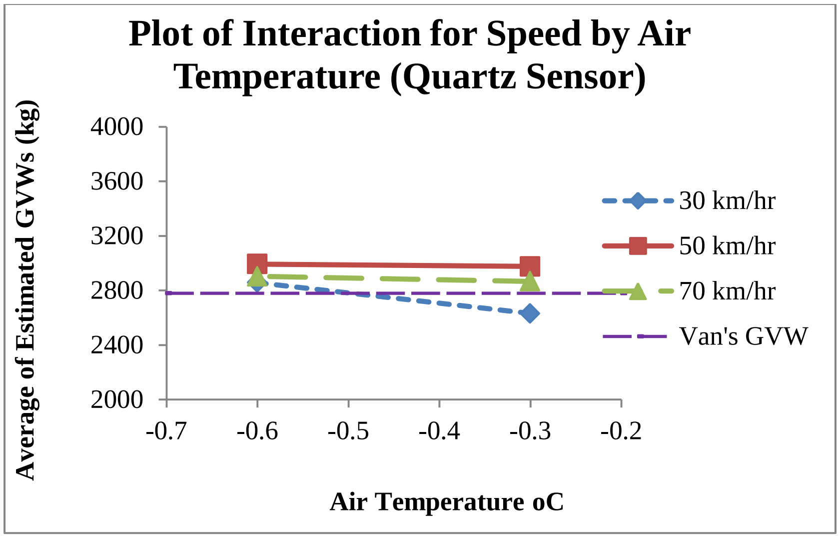


Figure 4-20– The interaction for speed by air temperature for the recalibrated quartz sensors

4.2.4.2 The Polymer Sensor

The polymer sensors' data arrangements are displayed in Table B. 18 (Appendix B). The analysis of variance computations (Table B. 19) show that speed has significant effect on sensors since the results at speeds lower than 30 km/hr are still significantly different from higher speeds. The lines in Figure 4-21 illustrate negligible interaction between speed and temperature. A normal probability plot of the residuals (Figure B. 8) and standardized residual computations demonstrated no severe deviations from normality and no outlier, so that all residuals are in the range of a normal distribution.

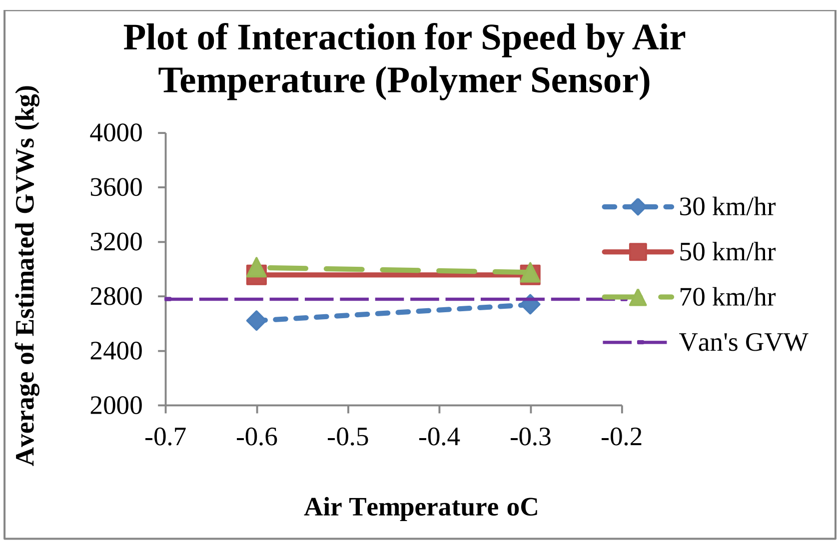


Figure 4-21– The interaction for speed by air temperature for the recalibrated polymer sensors

Since the polymer sensors had been working under the auto-cal setting in the first day of experiment, sensitivity of the sensors to speeds less than 30 km/hr is proved. Also, the estimations seem to be more consistent and closer to the van's static GVW at higher speeds.

4.2.4.3 The Ceramic Sensor

The ceramic sensors' data arrangements are displayed in Table B. 20 (Appendix B). The analysis of variance computations (Table B. 21) show that no factor has significant effect on recalibrated sensors. The crossed lines in Figure 4-22 illustrate very weak interaction between speed and temperature in speeds lower than 30 km/hr and negligible interaction in higher speeds. A normal probability plot of the residuals (Figure B. 9) and standardized residual computations demonstrated no severe deviations from normality and no outlier.

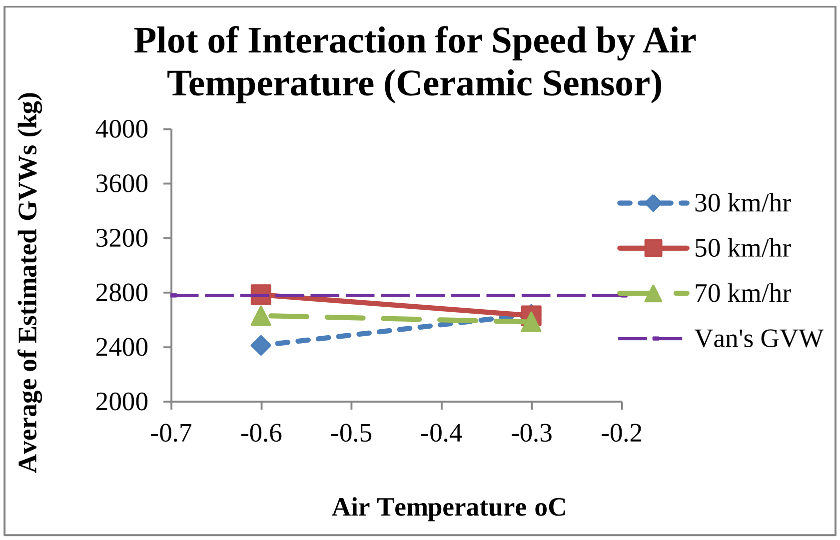


Figure 4-22– The interaction for speed by air temperature for the recalibrated ceramic sensors

4.2.5 Recalibration Results

Means of the WIM sensors' estimated GVWs in each factor level, the percentage difference between the mean values and the test vehicle's static GVW, and the summary results of the ANOVA computations in March 03 and 04, 2009, presented in Table 4-5 to Table 4-7. All sensors show improvements in estimations of GVWs in most of the factor levels after the recalibration. The significant effect of speed on the quartz sensors has changed to moderately significant and the same effect on the ceramic sensors has changed to no effect, after recalibration. The effect of speed on the polymer sensors is very strongly significant in both days, considering the sensors had been working under the auto-cal process on March 2009. The 20km/hr increment seems to be big in detection of the speed effects specifically for the quartz and polymer sensors. Air temperature demonstrates negligible effects on the performance of the quartz and ceramic sensors before and after the recalibration indicating that 0.3 to 0.5^{o}C bin sizes for the levels between -11 to zero degree of Celsius are not big enough to show the real effects specifically on the ceramic sensors. Since the polymer sensors were operating under the vendor's auto-cal process on March 03, no effect of this factor could be expected on this day. The 2^{o}C bin size in the temperature experiment seems to be suitable to detect the effect of this factor specifically on the polymer and ceramic sensors.

4.2.6 Conclusions and Recommendations

According to the analysis of the effects of temperature, speed and path run on the performance of piezoelectric WIM sensors, the following conclusions and recommendations can be discussed:

1. The test for the effects of temperature and speed in May 2008, demonstrated that the polymer and ceramic sensors are susceptible to air temperature while the quartz sensors remained insensitive. None of the sensors demonstrated susceptibility to speed at the speeds close to the speed limit at the WIM site (40 km/hr) considering 2 km/hr increments (Table 4-5),
2. The effect of temperature on the polymer sensors cannot be assessed since the auto-cal option was in effect during the tests in March 2009. However, the sensitivity was observed in the 2008 experiment (sec. 3.1.3.6). Negligible effects of temperature on the quartz and ceramic sensors in cold temperatures (less than 0^{o}C) suggests a 2^{o}C temperature level size for these sensors for the future research. The tests on May 2008 demonstrated that a 1^{o}C increment seems to be proper for tracking sensitivity to temperature factor when air temperatures are between 5 ^{o}C and 20^{o}C,
3. The test for the effects of path run and air temperature factors demonstrates that path run has a significant effect on all sensors specifically on the quartz and ceramic sensors. Since the polymer sensors was operating under the auto-cal process during the tests in March 2009, the moderate effect of this factor on the polymer sensors can be considered as the effect of transverse location of vehicle's axle on the calibrated sensors in both test days (Table 4-6),
4. The effect of interaction between path run and temperature is significant for the ceramic sensors before the recalibration; the estimates can have errors of approximately 0% to 40%. This effect for the polymer sensors, which were operating under the vendor's built-in auto-calibration process, is still significant. However, the GVW estimations can have errors of less than 11%,
5. Sensitivities to speed for the quartz and polymer sensors are mainly to speeds lower than 30 km/hr even after recalibration (Table 4-7),
6. To avoid the VSS effect of interaction between factors specifically path run and temperature, at least two recalibrations per year is recommended for the piezoelectric WIM sensors which are operated under manual calibration process.

Table 4-5– ANOVA summary in the temperature experiment including the means of GVW estimations and errors at factor levels

			Quartz Sensor				**Polymer Sensor**				**Ceramic Sensor**			
		Level	**GVW**	**%**	**Effect**	**Cross**	**GVW**	**%**	**Effect**	**Cross**	**GVW**	**%**	**Effect**	**Cross**
28-May-08	**(ºC)**	**8 to 9.99**	2623.3	-5.6%	VW		2109.2	-24.1%	**VSS**		1134.0	-59.2%	**VSS**	
		10 to 11.99	2570.4	-7.5%			2676.2	-3.7%			1753.9	-36.9%		
		12 to 13.99	2608.2	-6.2%			2955.9	6.3%			2623.3	-5.6%		
		14 to 15.99	2714.0	-2.4%			3190.3	14.8%			3144.9	13.1%		
		16 to 17.99	2585.5	-7.0%			2933.2	5.5%			3069.3	10.4%		
	Speed	**43 km/hr**	2606.6	-6.2%			2797.2	0.6%			2346.6	-15.6%		
		45 km/hr	2633.9	-5.3%			2748.8	-1.1%			2343.6	-15.7%		

Table 4-6– ANOVA summary in the path run experiment including the means of GVW estimations and errors at factor levels

			Quartz Sensor				**Polymer Sensor**				**Ceramic Sensor**			
		Level	**GVW**	**%**	**Effect**	**Cross**	**GVW**	**%**	**Effect**	**Cross**	**GVW**	**%**	**Effect**	**Cross**
03-Mar-09	**(ºC)**	**-11 to -9.5**	2491.0	-10.4%			2498.5	-10.1%	VW	**SS**	3122.2	12.3%	VW	**VSS**
		-9.5 to-8.0	2494.8	-10.3%			2547.7	-8.4%			3197.8	15.0%		
	Path Run	**Path Run 1**	2109.2	-24.1%	**VSS**		2579.8	-7.2%	**MOS**		2795.3	0.5%	**VSS**	
		Path Run 2	2710.2	-2.5%			2477.7	-10.9%			3912.2	40.7%		
		Path Run 3	2659.2	-4.3%			2511.8	-9.6%			2772.6	-0.3%		

Table 4-7– ANOVA summary in the speed experiment including the means of GVW estimations and errors at factor levels

			Quartz Sensor				Polymer Sensor				Ceramic Sensor			
		Level	**GVW**	**%**	**Effect**	**Cross**	**GVW**	**%**	**Effect**	**Cross**	**GVW**	**%**	**Effect**	**Cross**
03-Mar-09	**(ºC)**	**-6.99 to -6.5**	2439.3	-12.3%	W	VW	2293.2	-17.5%		W	3059.2	10.0%	VW	W
		-7.50 to -7.0	2509.9	-9.7%			2273.0	-18.2%			3175.1	14.2%		
	Speed	**30km/hr**	2131.9	-23.3%	**VSS**		2154.6	-22.5%	**VSS**		2593.0	-6.7%	**VSS**	
		50km/hr	2608.2	-6.2%			2313.3	-16.8%			3197.8	15.0%		
		70km/hr	2683.8	-3.5%			2381.4	-14.3%			3560.7	28.1%		
04-Mar-09	**(ºC)**	**-0.3 to 0.0**	2824.4	1.6%	VW		2890.9	4.0%			2618.7	-5.8%		VW
		-0.6 to -0.3	2918.1	5.0%			2863.7	3.0%			2609.7	-6.1%		
	Speed	**30km/hr**	2744.2	-1.3%	**MOS**		2680.7	-3.6%	**VSS**		2526.5	-9.1%		
		50km/hr	2984.6	7.4%			2957.4	6.4%			2707.9	-2.6%		
		70km/hr	2884.8	3.8%			2993.7	7.7%			2608.2	-6.2%		

4.3 Performance of Sensors under Typical Traffic Stream

More than 10,000 vehicles including class 6 garbage trucks (Figure 4-23) at the Landfill site (July to October 2008) and over 7,000 class 9 trucks (Figure 4-24) at the Highway 401 site (5 to 11 November 2010) analyzed to explore the effects of traffic and climate on the piezoelectric WIM sensors. Figure 4-23 and Figure 4-24 illustrated vehicle classifications at the Landfill and Highway 401 sites. The frequent vehicle at both sites account for 35% to 40% of the total vehicles passed over the sensors. The data collections from July to October 2008 at the Landfill site and in November 2010 at the Highway 401 site were right after calibration of MS-WIM systems, when the pavements at both sites were at best conditions and the sensor systems were at the start of their service lives.

Figure 4-23- The FHWA's class 6, garbage truck, the Landfill site

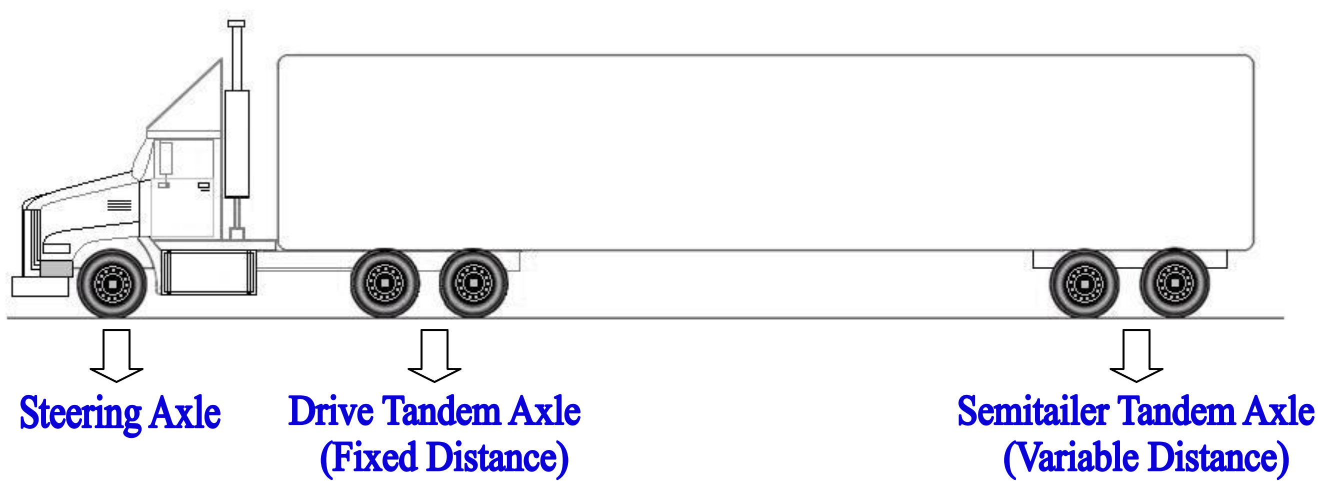


Figure 4-24- The FHWA's class 9, 3S2 (3-axle tractor, 2-axle semitrailer) truck, the Highway 401 site

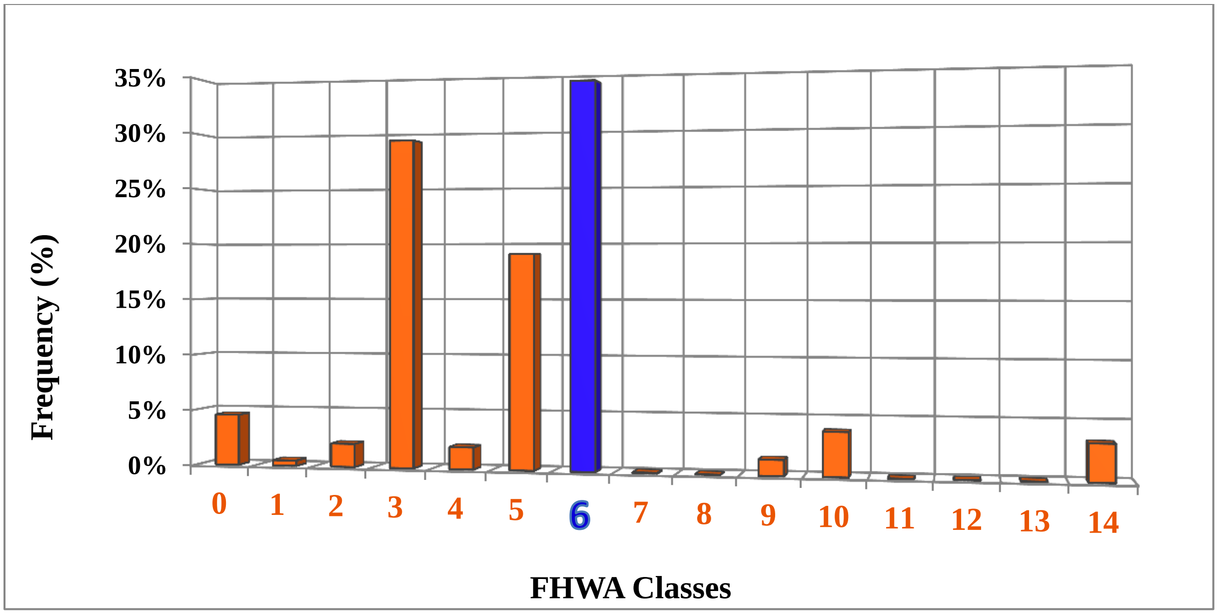


Figure 4-25- Vehicle Classification and the frequent truck (class 6), the Landfill site in July 2010

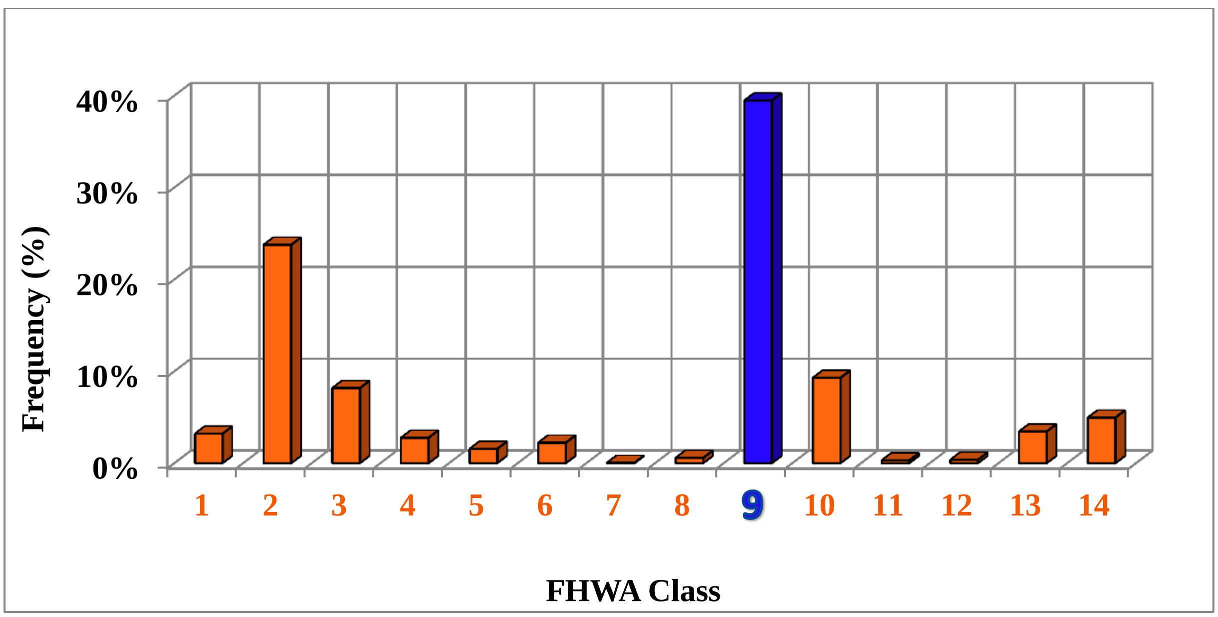


Figure 4-26- Vehicle Classification and the frequent truck (class 9), the Highway 401 site in November 2010

4.3.1 Load Spectra at the WIM Sites

The gross weight load spectra at the Landfill and Highway 401 sites follows bimodal load patterns (including two peaks for unloaded and loaded trucks). Figure 4-27 illustrates the gross weight spectrum of the FHWA class 6 garbage trucks at the Landfill site constructed by the quartz sensor data. Figure 4-28 illustrates the gross weight spectrum at the Highway 401 WIM site. The 16 tons unloaded peak is reasonable; however, the 28 tons loaded peak sounds to have been underestimated approximately -15% to -25% since the loaded trucks should be under maximum permitted GVW on Canada and the US highways (less than 36.5 tons (80,000 lb) or between 32 and 36 tons). The possible reason for this is that the sensors were calibrated using a light truck with axle weights less than 2 tons.

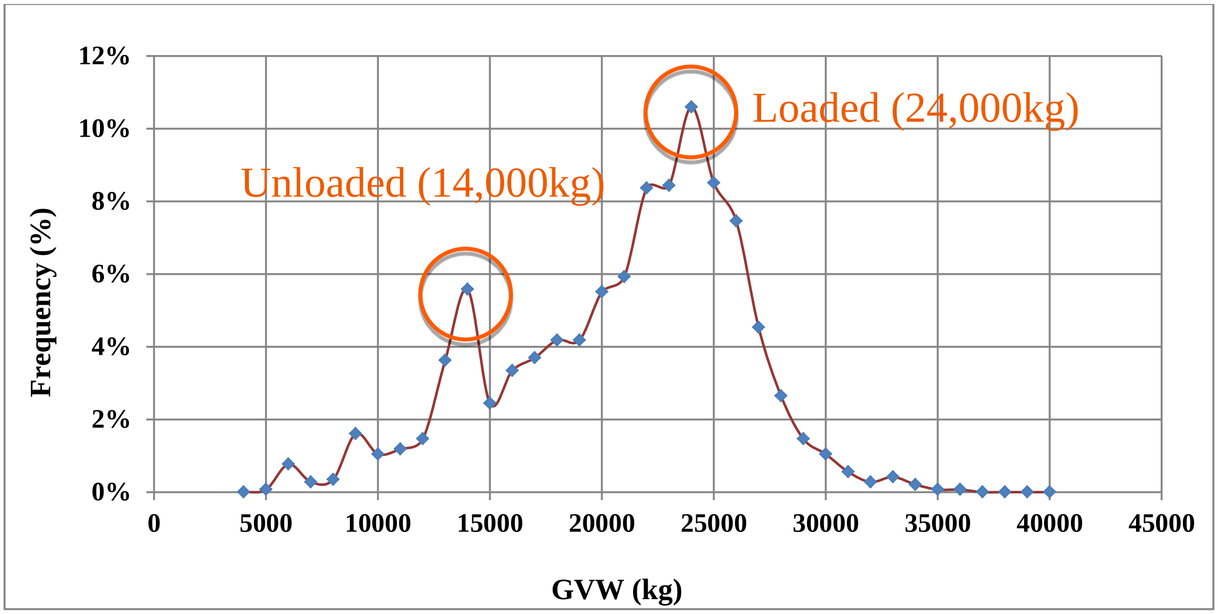


Figure 4-27- Gross weight spectrum of class 6 trucks by quartz sensor, the Landfill site in July 2008

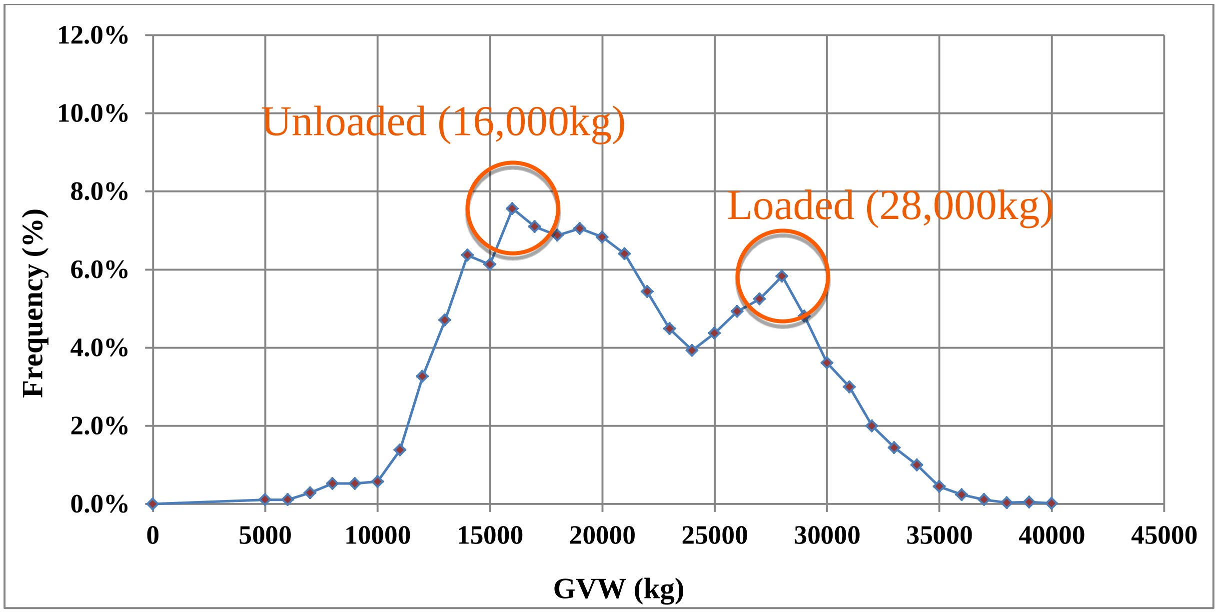


Figure 4-28- Gross weight spectrum of class 9 trucks by polymer sensor, the Highway 401 site in November 2010

4.3.2 Investigations on Axle Weights of Classes 6 and 9 at the Highway 401 Site

The class 9, 3S2 trucks are used for WIM sensor calibration at the Highway 401 site, since it represents the most frequent class of trucks on North American highways. Axle weights of two types of frequently loaded Canadian trucks are shown in Table 4-8.

Table 4-8- Typical static axle loads and GVW of Class 9 loaded trucks

3S2-Load	Unit	Steering Axle	Drive Tandem	Rear Tandem	GVW
Typical Heavy	Lb	11900	33000	32500	77400
	Kg	**5398**	**14969**	**14742**	**35108**
Typical Light	Lb	11700	31100	28700	71500
	Kg	**5307**	**14107**	**13018**	**32432**

The trucks' are normally loaded with foods and vegetables including typical heavy loads such as carrot, potato, onion, fruits, etc. and typical light loads (more volume, less weight) such as lettuce, mushroom, etc. Any of these sample data can be used as a characteristic truck for the WIM auto-calibration feature at WIM system. Table 4-9 shows axle and gross weights of unloaded class 9 trucks. These numbers are used for validating the unloaded part of axle load spectra. Class 6 trucks, which are discovered to be mostly tractors of the five axle trucks (Cab-over Engine (COE) or Cab-over) were analyzed for checking the current calibration status of the CPATT's polymer sensor. The COEs on highways are normally in the minimum size and weight category of class 9 tractors (such as day-cabs) and used for taking the loaded semi-trailers for local transportations. Table 4-10 shows axle and gross weights of Volvo (Typical heavy) and Freightliner (Typical light), which are two manufacturer of COEs.

Table 4-9- Axle loads and gross weights of Class 9 unloaded trucks

3S2-Unload	Unit	Steering Axle	Drive Tandem	Rear Tandem	GVW
Typical Heavy	Lb	10700	13000	9550	33250
	Kg	**4853**	**5897**	**4332**	**15082**
Typical Light	Lb	9000	12000	9550	30550
	Kg	**4082**	**5443**	**4332**	**13857**

Polymer piezoelectric WIM estimations for steering axle and gross weight averages of the COEs on the Highway 401 site in November 2010 were compared with numbers in Table 4-10. Table 4-11 shows that the polymer piezoelectric sensors underestimate both steering axle and gross weights. It seems that the sensors are in good shape with absolute differences about 10% to 15% and less than 5% for steering axle and gross weights respectively for the weights less than 9 tons.

Table 4-10- Typical axle and gross weights of COE trucks

Cab-over	Unit	Steering Axle	Drive Tandem	GVW
Typical Heavy	Lb	10750	9050	19800
	Kg	**4876**	**4105**	**8981**
Typical Light	Lb	9000	8100	17100
	Kg	**4082**	**3674**	**7756**

Table 4-11- Typical COEs' steering axle and gross weights estimated by polymer piezoelectric, Nov. 2010

WIM				
Cab-over	**Steering**	**%**	**GVW**	**%**
Typical Heavy	9480 lb	**-12%**	19401 lb	**-2%**
	4300 kg		**8800 kg**	
Typical Light	7716 lb	**-14%**	16314 lb	**-5%**
	3500 kg		**7400 kg**	

Polymer piezoelectric WIM estimations for axle spacing show that approximately (69-74)% and (86-87)% data for the Cab-Over and 3S2 trucks in March and April 2011 have a drive axle spacing in the range of 1.28 to 1.40 meter (4.20 to 4.59 feet) respectively, which indicates an acceptable axle spacing calibration at the Highway 401 site.

4.3.3 Sensor Performance in Different Weight Categories at the Highway 401 Site

The polymer piezoelectric sensors data in November 2010 and according to the conditions mentioned above were selected and averages of axles in each tandem axle were calculated. Regression between steering axle and average of axles at drive tandem and also between steering axle and average of axles in the semitrailer's tandem (rear tandem) were constructed. Figure 4-29 and Figure 4-30 illustrate the regression between steering axle and average weights in the truck and semitrailer's tandem axles, which include both unloaded and loaded trucks. Changes in estimation can be inferred from the dashed lines, which also show heterogeneous variance of error with progress of weight. Therefore, relationship between the axle loads doesn't follow a first order regression model as it was discussed in section 4.3.2. shows that the linear regression model is not adequate.

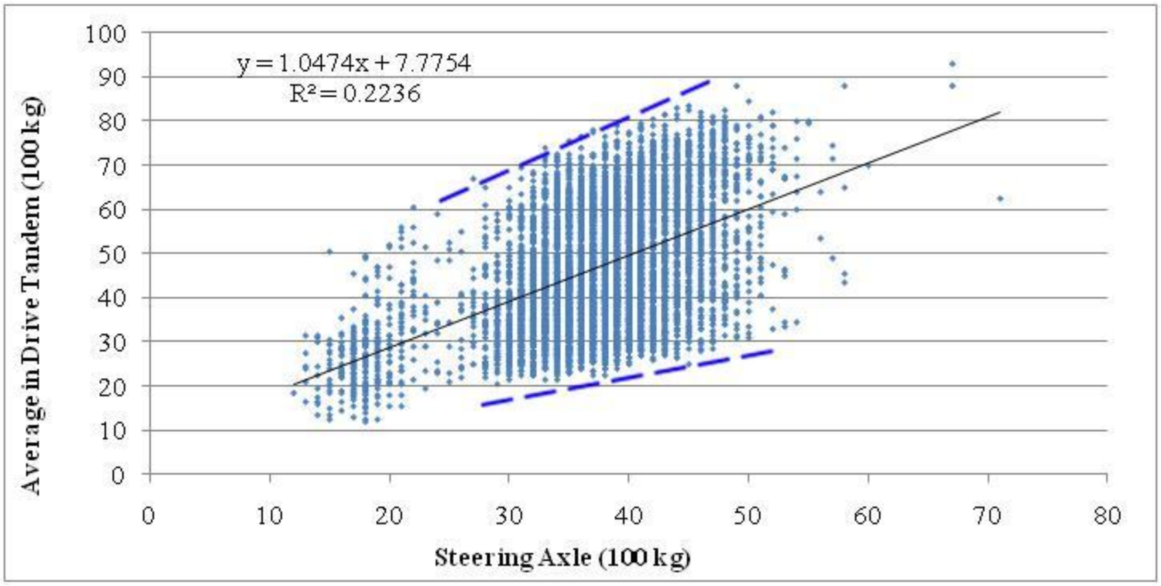


Figure 4-29- Polymer sensor estimates at different weight ranges, the Highway 401 site

4.3.4 Effect of Weight Factor on Polymer Piezoelectric Sensors at the Highway 401 Site

The data on November 2010 and on March 2011 from the Highway 401 site were statistically analyzed in order to investigate the effect of weight on the polymer piezoelectric sensors. To accomplish this, unloaded and loaded classes of trucks were separated from the database using mainly the frequency analysis. The reasons for this separation were to:

- Access unloaded axle weights which are closer to the axle weights of the CPATT van that was used for calibration,
- Investigate the effect of weight in different classes of truck weights, which would assist to observe this effect in two major load classes of 3S2 truck, and
- Facilitate investigation of the temperature factor, which means that different temperature classes can be studied in at least two major weight classes.

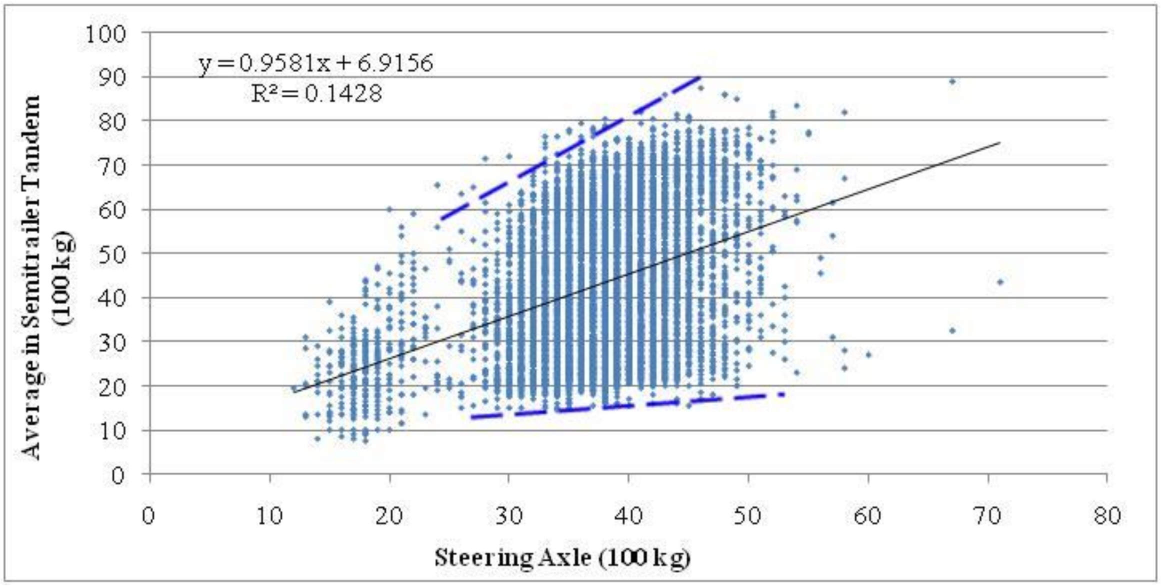


Figure 4-30- Polymer sensor estimates at different weight ranges, the Highway 401 site

In order to investigate the effect of weight in each load class, the relationship between steering axle and gross weights of the trucks was constructed and evaluated. The patterns of the cloud of data in both unloaded and loaded trucks are similar to a fan as discussed before with respect to the polymer piezoelectric data from the landfill site. The key difference between the sites is that in the Landfill site the static gross weights of the trucks are available from the static scale upstream from the WIM station; however at the Highway 401 site the only data available to this study were the updated unloaded and loaded axle weights of 3S2 trucks discussed in section 4.3.2.

The loaded and unloaded trucks were separated using the relationships between the axle load estimations by the polymer piezoelectric sensors (since the GVW of truck is just a summation of axle loads and not result of the sensor's estimation). Figure 4-31 and Figure 4-32 illustrate small difference in the regression models; however, in both graphs sensitivity of the sensor to the weight of trucks can be observed.

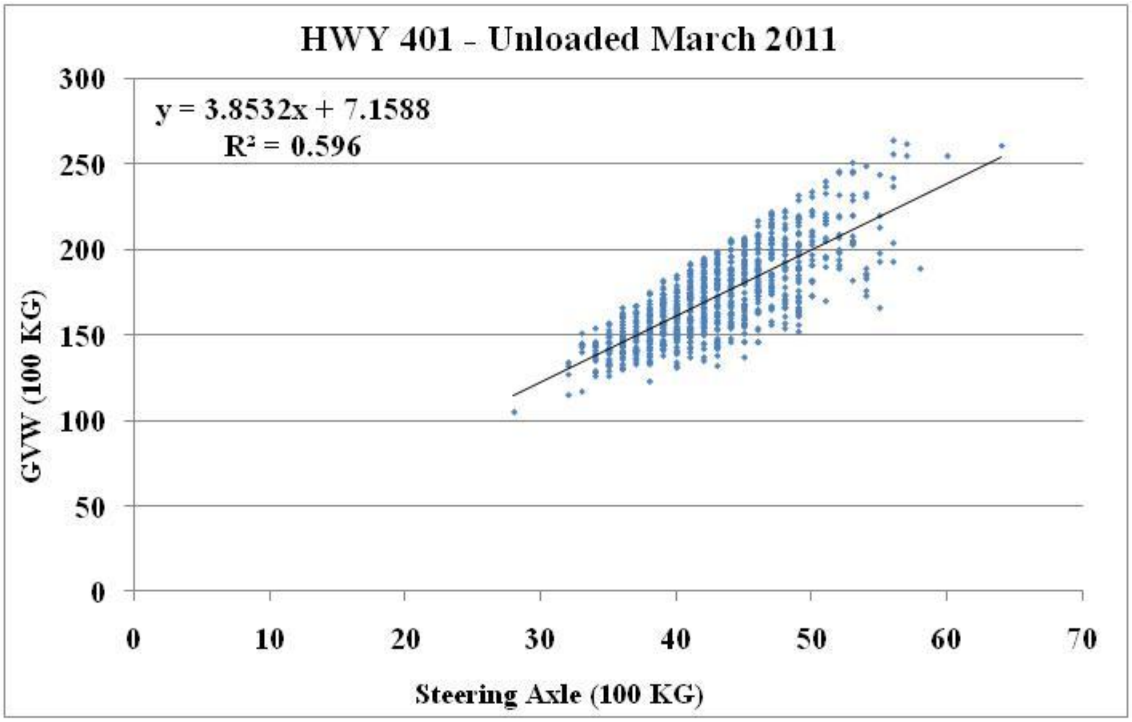


Figure 4-31- Steering axle versus GVW for unloaded data in March 2011, the Highway 401 site

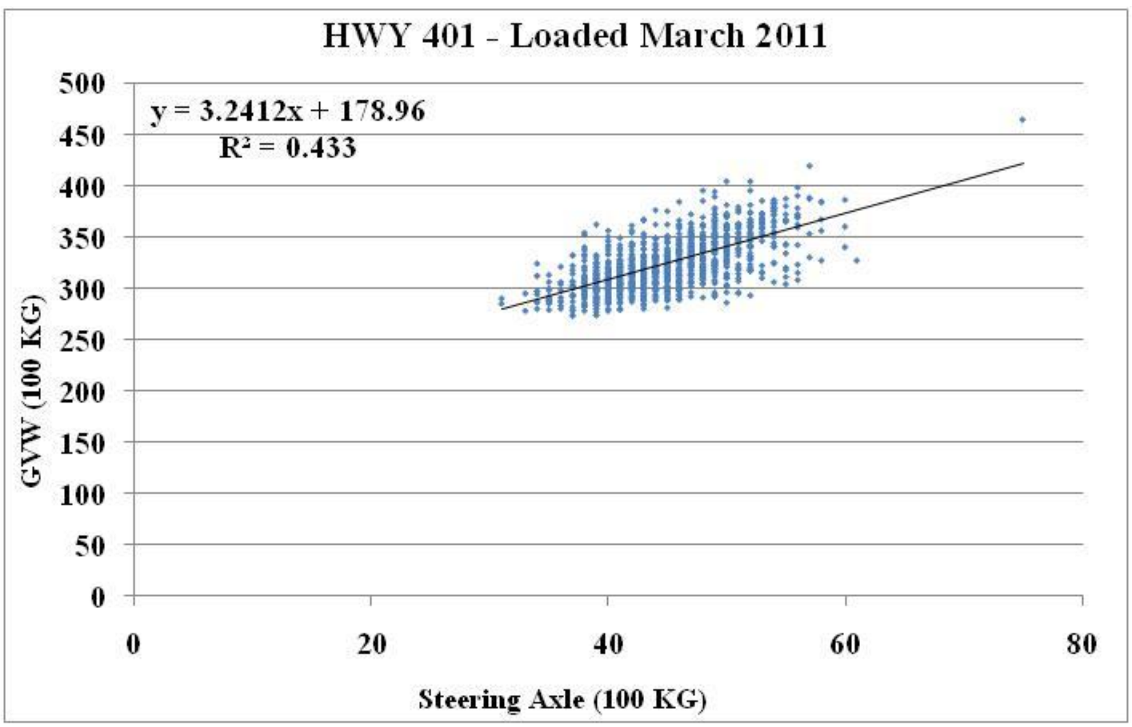


Figure 4-32- Steering axle versus GVW for loaded data in March 2011, the Highway 401 site

4.3.5 Effect of Weight Factor on Different WIM Sensors at the Landfill Site

The matched data between the static scale and WIM station at the landfill site were analyzed to investigate the performance of different piezoelectric WIM sensors using the natural traffic stream at this site (see Appendix C for the matching procedure). The garbage trucks that passed over the WIM sensors at the Landfill site were expected to be all fully loaded. Considering the static GVW analyses executed in 2009 (Appendix C), difference between tare and gross weights can change in the range of 1.5 to 5.0 tons. Therefore, light or unloaded and heavy or loaded trucks were filtered from the matched data for October 2008 using this criterion. Figure 4-33 to Figure 4-35 illustrate the relationship between static GVW and the estimations by polymer, quartz and ceramic piezoelectric sensors respectively, in the total sample space of approximately 1925 matched data in July 2008 and for the estimations with less than 50% error. By removing some of the lighter or unloaded vehicles from the July 2008 data, the relationship between static scale measurements and polymer sensor estimations in the sample spaces of "heavy or loaded" vehicles can be seen in Figure 4-36.

To prove that the estimations by polymer piezoelectric sensors do not have a constant variance, the standardized residuals of the estimation were plotted against the predicted value of GVW based on the data and the model regression in Figure 4-33. The figure illustrates that by increasing the load over the polymer piezoelectric sensors the error residuals were changed. Therefore, the variance of estimations is not constant. Decrease of the slopes of the regression models from July to November 2008 shows a relationship with falling the air temperature (Table 4-12). According to the analyses and data on Table 4-12, the following results can be concluded:

1. The polymer piezoelectric system tends to underestimate the axle loads,
2. Static GVW and polymer sensor estimation have not a linear relationship,
3. The errors seems to progress multiplicative rather than additive with magnitude of weight, and
4. Transformations of parameters are required to stabilize the variance of error

Table 4-12- Static versus polymer piezoelectric estimation of GVW of traffic stream at the Landfill site

2008 Data	**Slope of Regression Model (all Data)**	**Count**	**Slope of Regression Model (Loaded trucks)**	**Count**	**Average Daily High Air Temperature**	**Average Daily Low Air Temperature**
July	0.88	1959	0.80	749	25.7 °C	15.3 °C
August	0.88	1971	0.85	755	24.1 °C	13.1 °C
September	0.88	2767	0.81	1136	21.7 °C	10.3 °C
October	0.78	2913	0.72	1062	13.4 °C	2.5 °C

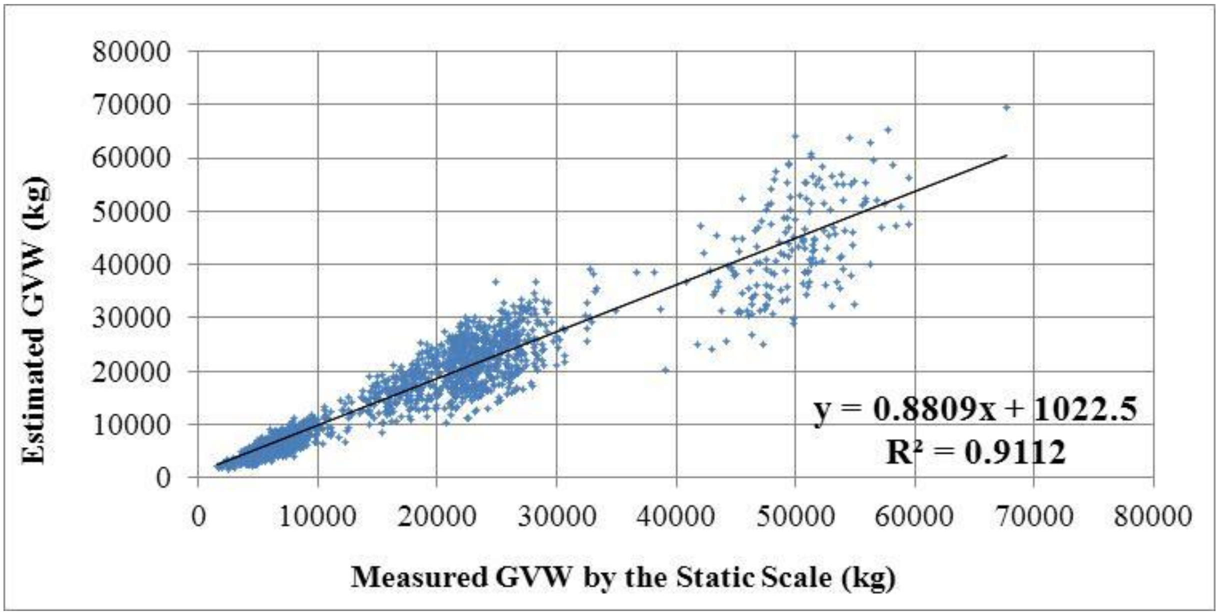


Figure 4-33- Static GVW versus polymer piezoelectric GVW estimation for all matched vehicles, the Landfill site in July 2008

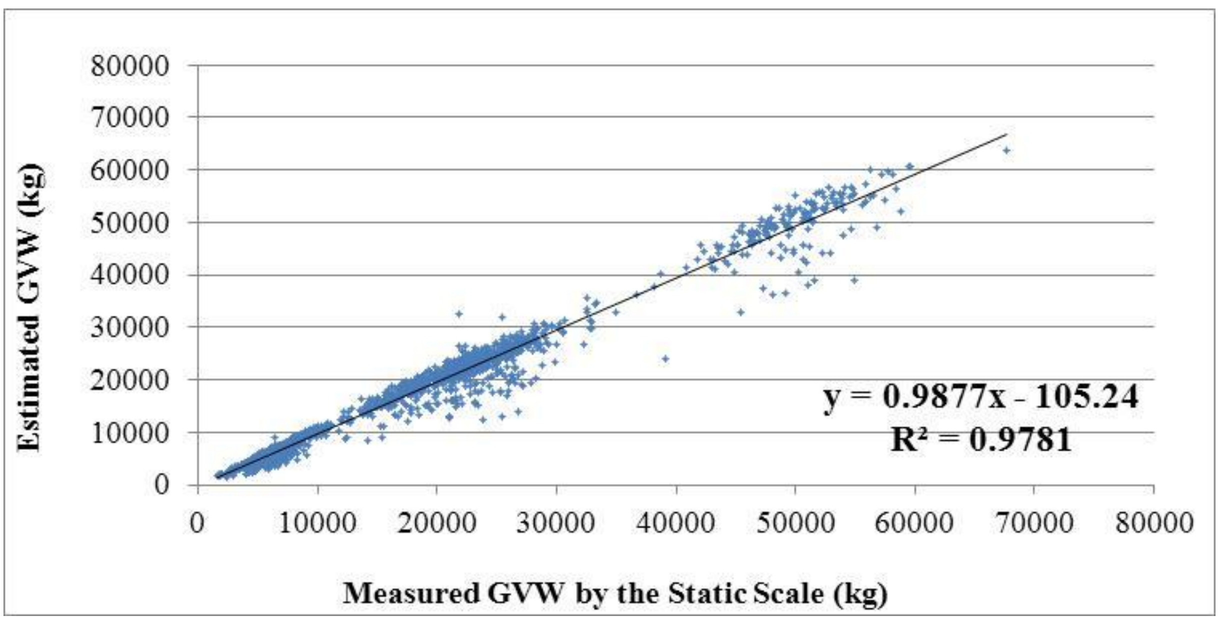


Figure 4-34- Static GVW versus quartz piezoelectric GVW estimation for all matched vehicles, the Landfill site in July 2008

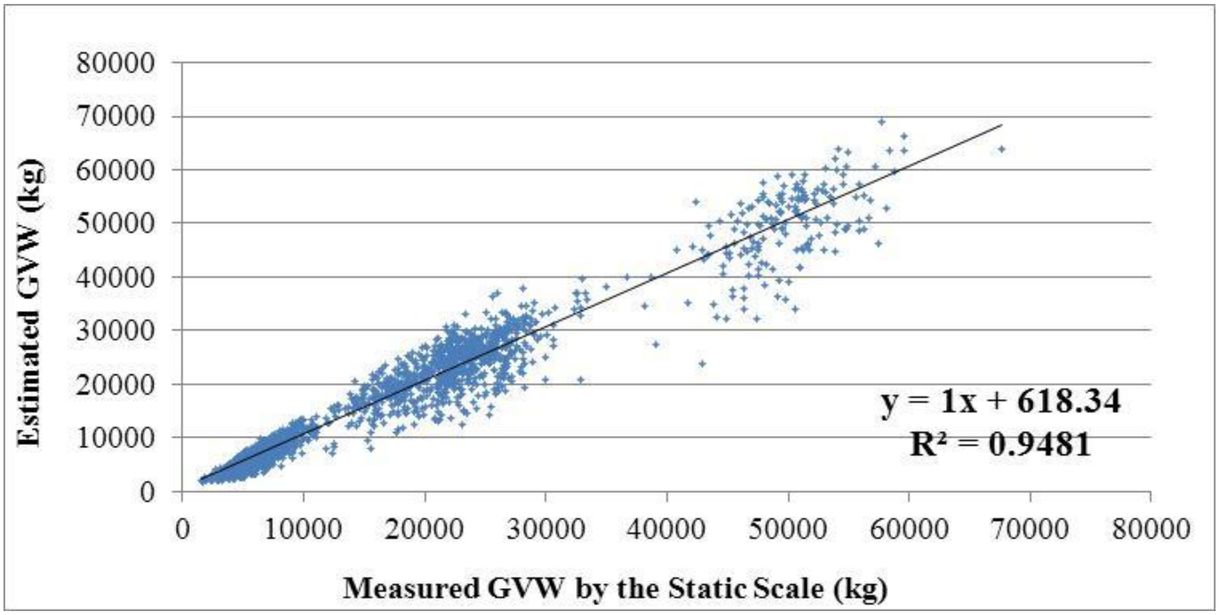


Figure 4-35- Static GVW versus ceramic piezoelectric GVW estimation for all matched vehicles, the Landfill site in July 2008

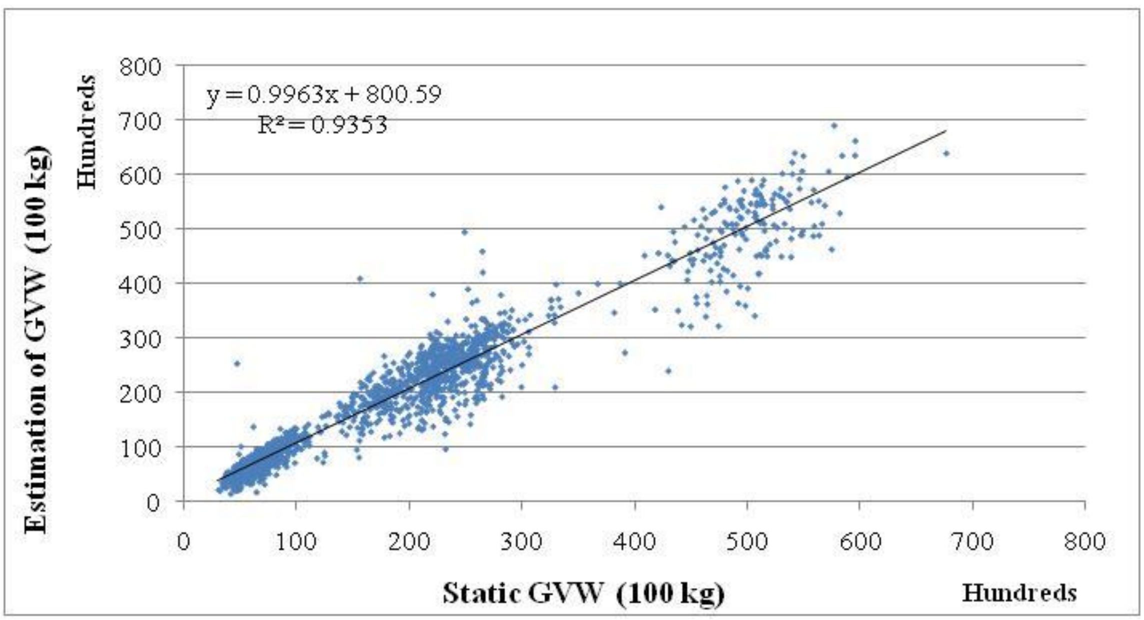


Figure 4-36- Static GVW versus polymer piezoelectric GVW estimation for matched heavy trucks, the Landfill site in July 2008

4.3.5.1 Assessing the Adequacy of the Regression Model

In almost all cases, the accurate relationship between the Y and X variables cannot be clearly defined, therefore a regression model is an approximate function of fitting to data. The regression model is constructed based on various assumptions. For instance, the differences between actual observations and the corresponding fitted values calculated from the regression model called residuals must be uncorrelated random variables with mean zero and constant variance (N[0,σ^2]). In addition, if a linear model is fitted to the data then it is assumed that variables X and Y are related in a first order manner.

As it was discussed, Figure 4-37 shows a pattern, which has a typical issue of changing variance with the magnitude of the weight factor. A typical solution to this problem is transformation of data that may stabilize the variance of errors of observations. This research thesis applied the Box and Cox method to calculate the best transformation for polymer sensor estimations and for static gross weights.

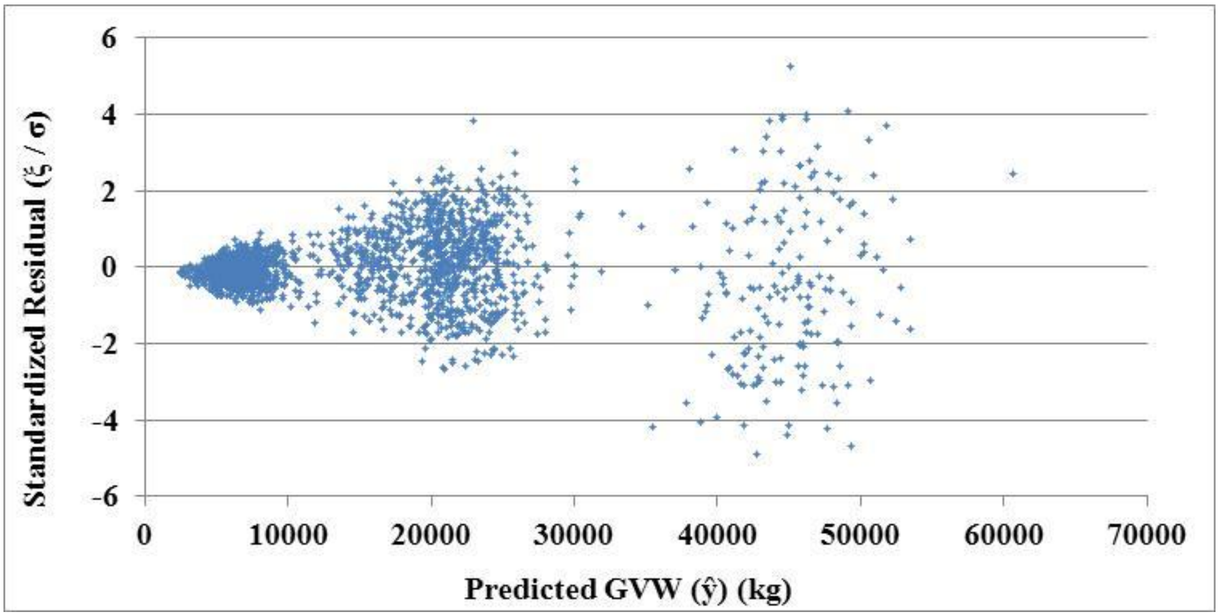


Figure 4-37- Polymer piezoelectric standardized residuals against predicted value of GVW (adequacy check for the regression model in Figure 4-33)

4.3.5.2 Data Transformation Using the Box and Cox Method

An analysis of transformation (Box, Cox 1964) was performed on the Landfill site's July 2008 data where the static gross weights of trucks are available upstream of the Landfill WIM site. The analyses transform each parameter by selecting the best "λ" (lambda) using Equation 3:

$$y^{(\lambda)} = \begin{cases} \dfrac{y^{\lambda} - 1}{\lambda} & \lambda \neq 0 \\ \log(y) & \lambda = 0 \end{cases}$$

Equation 3- Box and Cox transformation (Box, Cox 1964)

To calculate the lambda, first the transformation in Equation 4 (Mason, Gunst & Hess 2003)should be made:

$$z^{(\lambda)} = \begin{cases} \dfrac{y^{\lambda} - 1}{\lambda \dot{y}^{\lambda - 1}} & \lambda \neq 0 \\ \dot{y} \log(y) & \lambda = 0 \end{cases}$$

Equation 4- Transformation formula to $z^{(\lambda)}$

Where: $\dot{y} = \text{Geometric Mean} = [\prod_{i=1}^{n} y_i] = \sqrt[n]{y_1 y_2 \cdots y_n}$

The maximum likelihood estimates for lambda (λ) were estimated by changing lambdas (λ) in the range of [-3 to +3] to minimize the Residual Sum of Squares (RSS) (Equation 5) or maximize the Logarithmic Likelihood Function (LLF) (Equation 6) using the SOLVER tools in Excel®.

$$(S(\lambda, z)) = SS_E = \sum_{i=1}^{n} (z_i^{(\lambda)} - \hat{z}_i^{(\lambda)})^2$$

Equation 5- Residual Sum of Squares

$$(f(x,\lambda)) = \frac{-n}{2} \ln \left[\sum_{i=1}^{n} \frac{\left(z_i(\lambda) - \bar{z}(\lambda)\right)^2}{n} \right] + (\lambda - 1) \left[\sum_{i=1}^{n} \ln y_i \right]$$

Equation 6- The Logarithmic Likelihood Function (LLF)

Where: $\bar{z}(\lambda) = \frac{1}{n} \sum_{i=1}^{n} z_i(\lambda)$

The estimated lambdas (λ) for both parameters, which were estimated in both RSS and LLF methods for the polymer sensor estimation (dependent variable) and the static scale measurements (independent variable), were 0.045 and 0.013 respectively. Figure 4-38 illustrates the estimated lambdas at the maximum values of LLF for both variables.

Equation 7 is the 95% Confidence Interval (CI) formula for lambdas (based on calculation of SS_E in Equation 5), where α is 0.05 and ν is the degree of freedom. Since, there were more than 1900 record in the July 2008 database, the degree of freedom (ν) exceeds 1000 and the t distribution defined in Equation 7 became normal distribution. This means that the components $[t^2_{(\alpha/2)}/\nu]$ in both estimations were negligible and therefore, the estimated lambdas were meaningful and used for transforming the variables.

$$CI\ for\ (\lambda) = SS_E(\lambda) \left[1 + \frac{t_{\alpha/2}{}^2}{\nu} \right]$$

Equation 7- 100(1-α)% Confidence Interval for (λ)

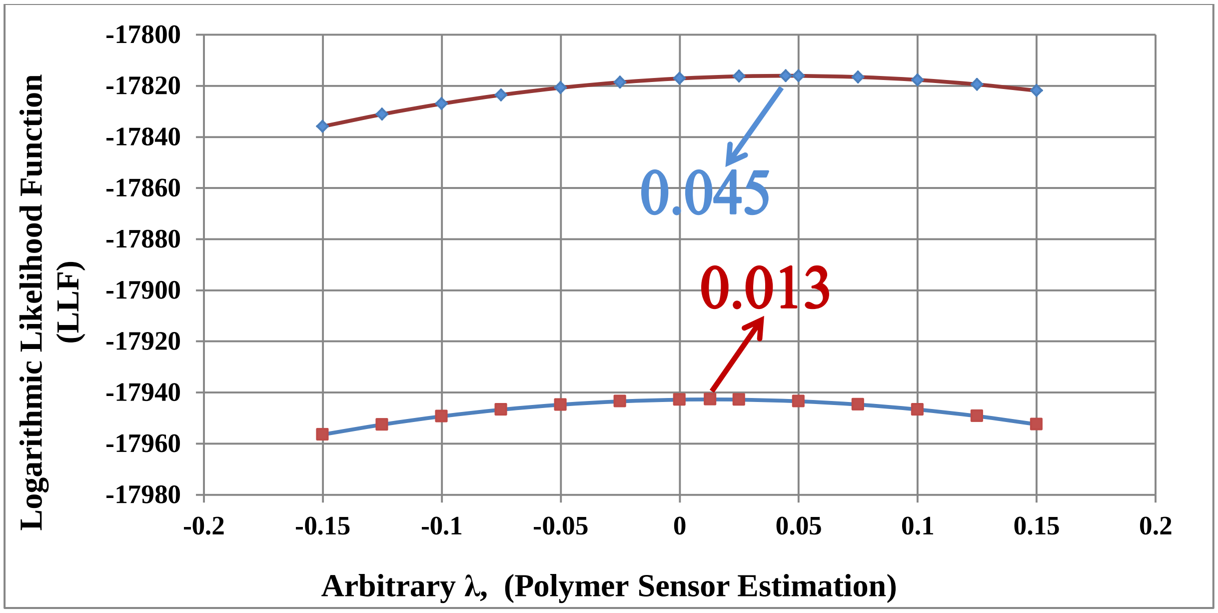


Figure 4-38- Lambdas for the polymer sensor estimation and static GVW transformations, the Landfill site

Transformation for the Static GVW (independent variable) is very close to zero, which means that a simple and reasonable logarithmic transformation solution can also be applied. However, the actual values of lambda resulted from this analysis were used for calculation of the corresponding transferred polymer sensor estimations and static scale gross weights. Figure 4-39 illustrates the normal probability plot of the transformed parameter (estimations), which shows no severe deviation from the normality. The distribution of data in Figure 4-40 illustrates no trend, which means that the variance of error has been stabilized after the transformations. Finally, Figure 4-41 shows a simple and adequate linear regression model between transformed parameters. As the values for slope and intercept are shown with their 95% confidence interval in the figure, both parameters of the model (slope and intercept) are meaningful at 95% confidence.

Table 4-13 illustrates that by changing the weight category of polymer sensor estimation by 10%, the model prediction will change almost the same 10%, therefore, the model works very well and consistent for the vehicle weights from 1 ton to 40 tons.

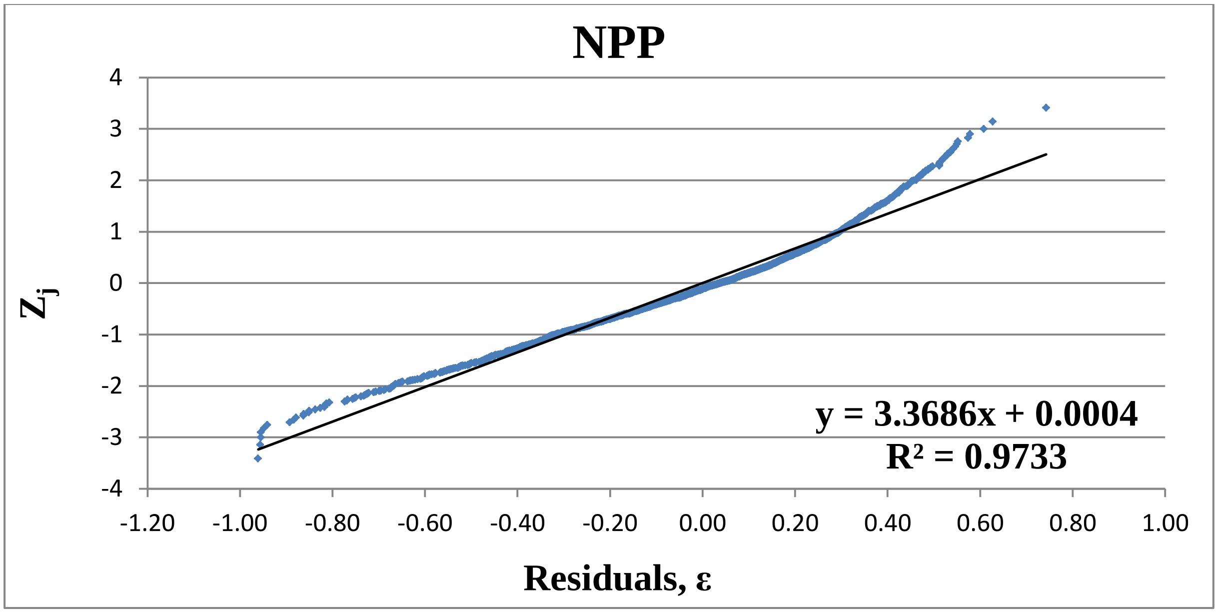


Figure 4-39- Normal Probability Plot of transformed polymer piezoelectric GVW estimations for the Landfill site, July 2008

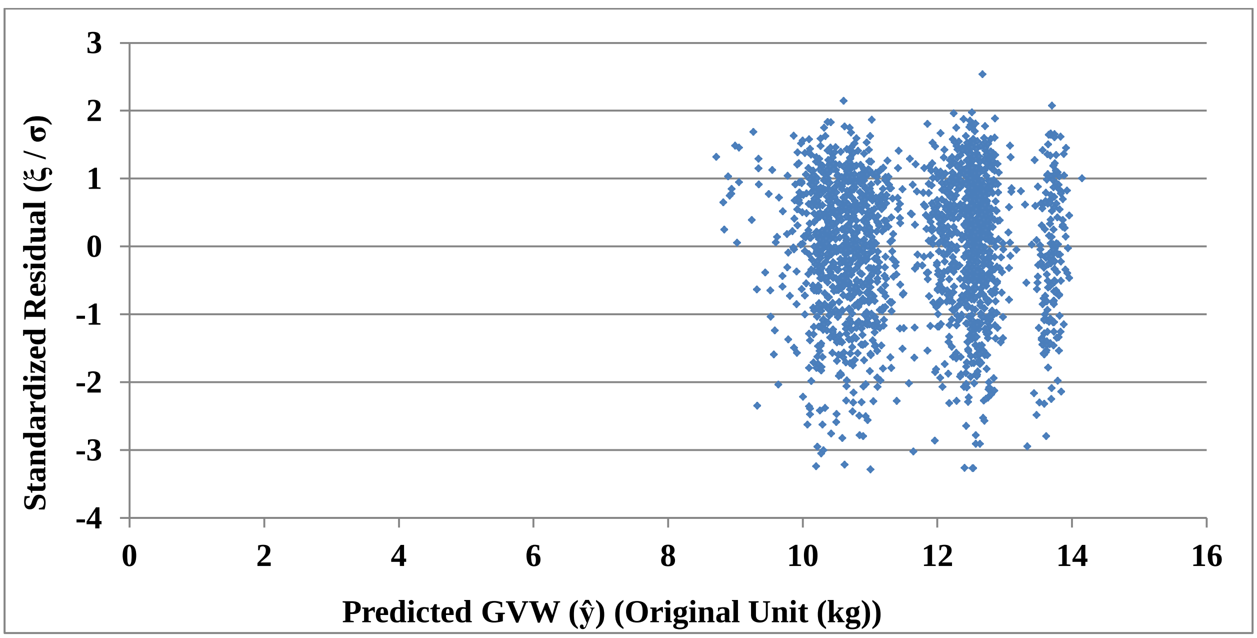


Figure 4-40- Stabilized variance of error of polymer sensor GVW estimations

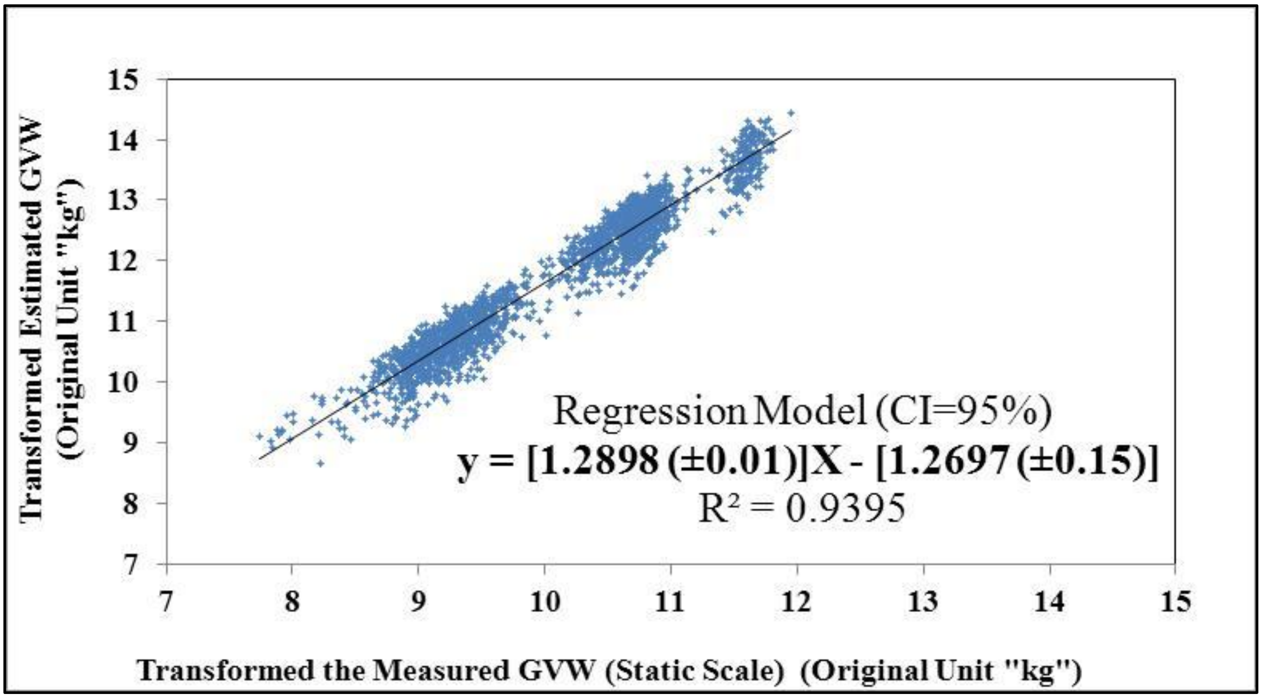


Figure 4-41- The regression model of polymer piezoelectric estimations after transformation, the Landfill site, July 2008

Table 4-13- Model Diagnostic for the Landfill Site, July 2008

Model Diagnostic		
Polymer Sensor Estimation	**Model Prediction**	**Difference (%)**
1000	1031.1	0.09
1100	1130.6	
10000	10347.7	0.09
11000	11425.8	
20000	21420.6	0.10
22000	23703.7	
30000	33025.5	0.10
33000	36592.1	
40000	45048.6	0.10
44000	49959.2	
50000	57423.4	0.10
55000	63728.1	

4.3.6 Validation of the Regression Model Using the Highway 401 Site Data

As it was discussed in section 4.3.1, the loaded peak in the gross weight spectrum for the trucks passed over the WIM system at the highway 401 site was approximately 20% underestimated by the polymer sensor. Since the pattern of air temperature in November 2010 was close to that in October 2008, the regression model for the Landfill data in October 2008 was constructed (Figure 4-42).

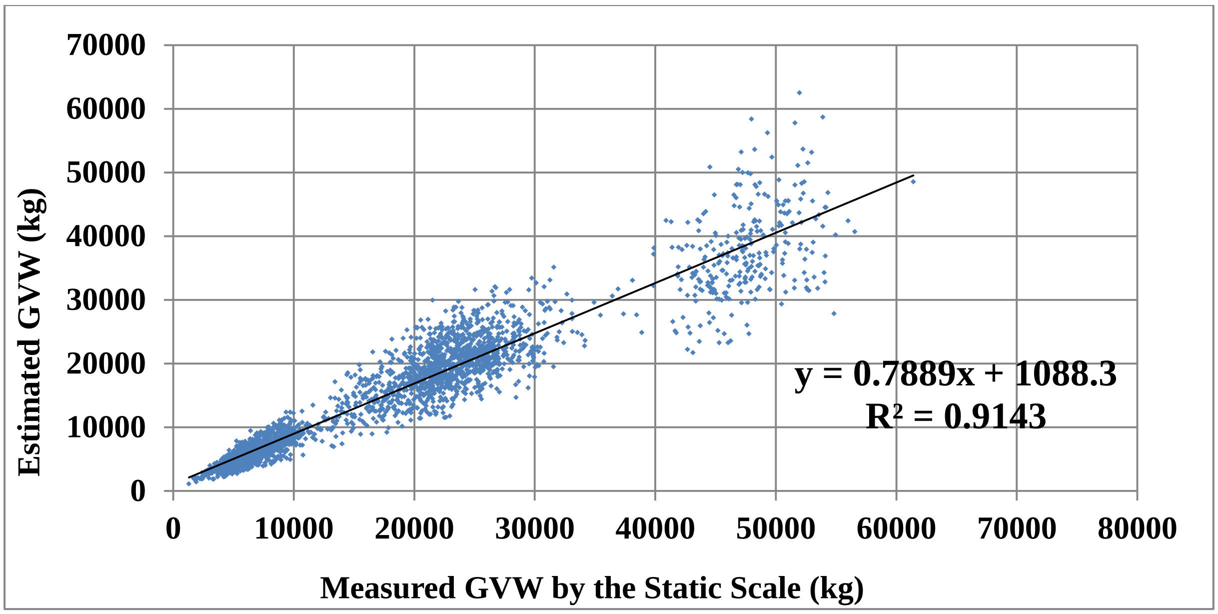


Figure 4-42- Static GVW versus polymer piezoelectric estimation for all matched vehicles for the Landfill site, October 2008

Using the Box and Cox method the lambdas transformations of the estimated GVW (polymer sensor) and static GVW were estimated 0.081 and 0.043 respectively. The regression models in July and October 2008 predicted 30,668.3 kg and 34,160.4 kg respectively for the second peak (GVW for the loaded class 9 trucks) in November 2010 (28,000 kg). The number predicted by the October model Figure 4-43, which had a similar pattern of air temperature in compare with the pattern in November 2010, seems very reasonable and is in the middle of the expected range of 32 to 36 tons.

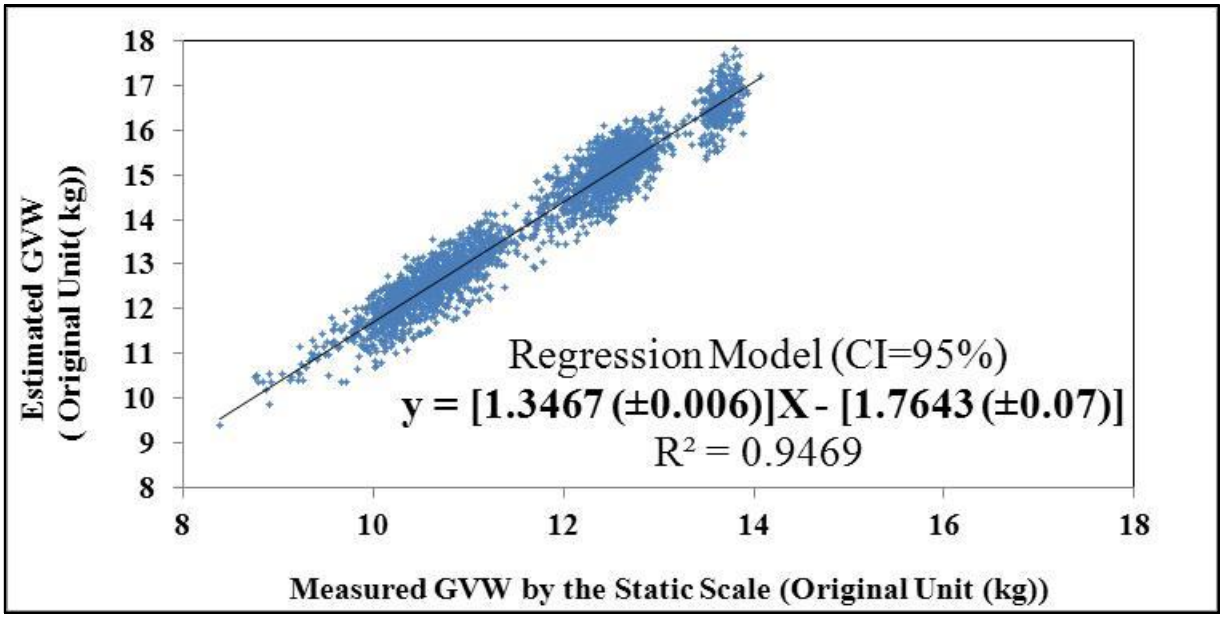


Figure 4-43- The regression model of polymer piezoelectric estimations after transformation for the Landfill site, October 2008

4.3.7 Sensor Performance in Different Air Temperatures at the Highway 401 Site

The polymer piezoelectric sensors data in November 2010 and according to the conditions mentioned above have selected, and the regression between steering axle and air temperature was constructed. Figure 4-44 illustrates that with changes in air temperature the output of polymer piezoelectric will change. Changes in estimations can be observed to increase more rapidly specifically in air temperatures higher than the calibration's air temperature, which was 6°C (Figure 4-45). This is mainly because the pavement temperature may change not as rapid as the air temperature change in November 2010. In temperatures higher than 6°C, the pavement temperature increased constantly as air temperature changed. This may be inferred that in the middle of fall season in southwestern Ontario, data connected to air temperatures 5°C to 15°C are most proper for temperature analysis.

In any case, the relationship is not linear. This information may be useful for making rapid corrections in an auto-calibration system rather than having to wait for significant shifts in load spectra (an approach that suffers from significant delays in many situations).

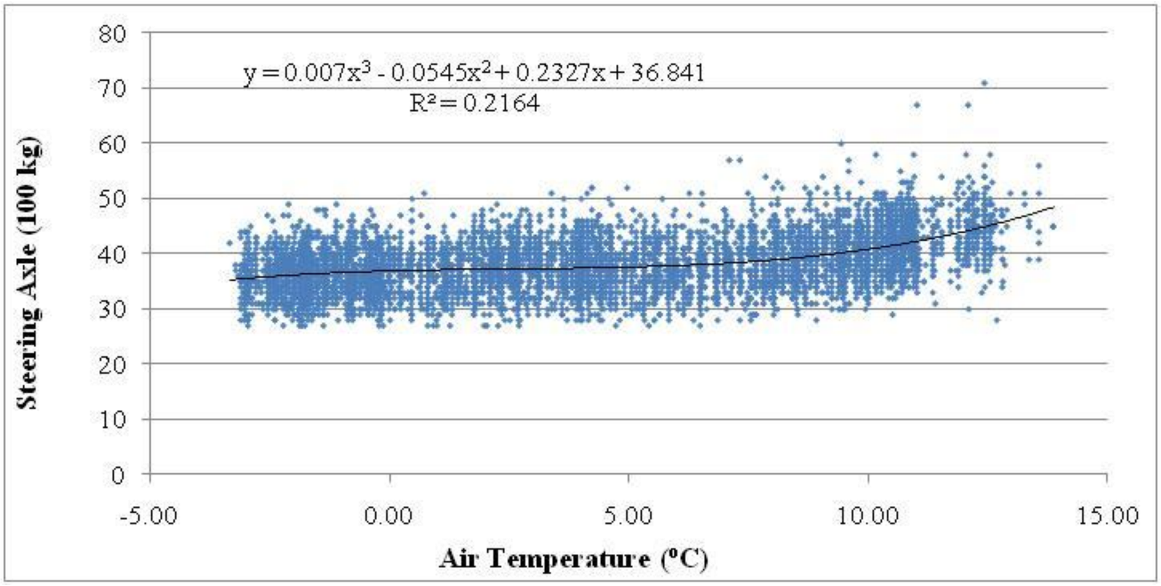


Figure 4-44- Polymer sensor estimates against air temperatures, the Highway 401 site

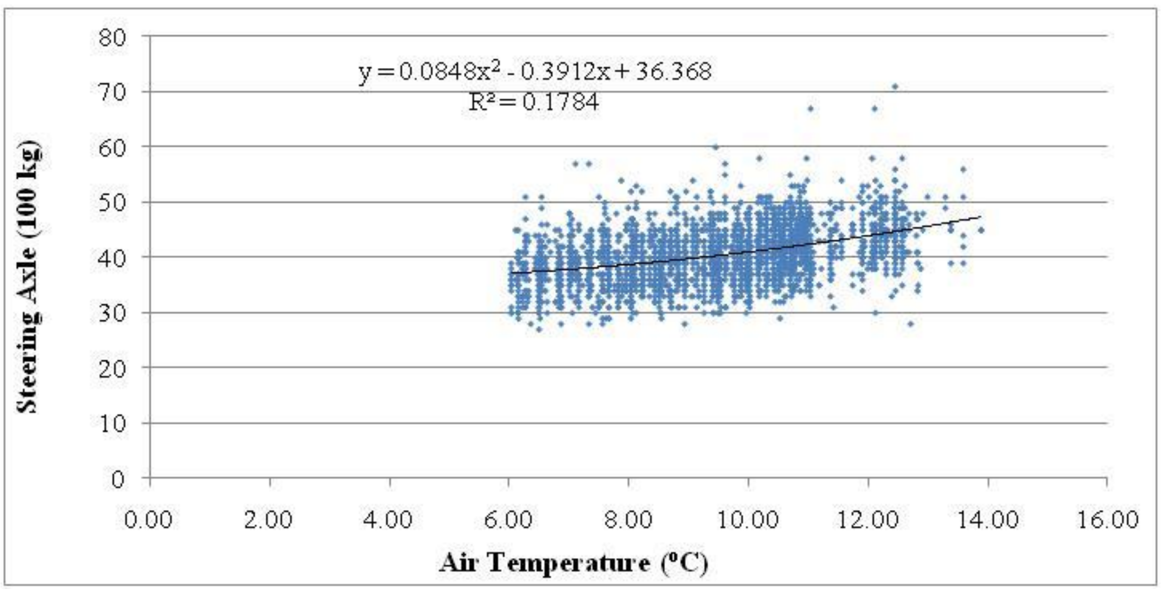


Figure 4-45- Polymer sensor estimates at air temperatures higher than 6^{o}C, the Highway 401 site

4.3.8 Sensor Performance in Different Speeds at the Highway 401 Site

The polymer piezoelectric sensors data in November 2010 and according to the conditions mentioned above were selected and a regression model between estimated steering axle weight and speed was constructed (Figure 4-46). Based on analysis of the Landfill data, more analysis should be done to track the true relationship between speed and weight estimation of the polymer piezoelectric sensors. However, it does not seem that the polymer piezoelectric sensors are significantly sensitive to the speeds close to the calibration speeds, such as 90 to 110 km/hr. This range seems to be the most frequent trucks' speed range on the truck lanes, as it has also been cited in a Canadian study which used WIM sensor data installed in southern Ontario for transportation planning (Hajek, Kennepohl & Billing 1992). The calibration of the sensors was performed in the range of 98 to 102 km/hr. However, given the frequent congestion along the highway 401, adjustment factors for slower speeds would have some use and value.

4.3.9 Data Preparation

The conditions for data preparation are as follow:

- Only the polymer piezoelectric data was selected since the quartz sensor's board at the cabinet still needs to be fixed for producing speed and correct estimations.
- Five axle Trucks 3S2 (three axle tractor-2 axle semitrailer), Class 9 FHWA, sub-classes: 37 and 38, were selected for data analyses,
- Only data was used for which the differences between the WIM sensor estimates on the first row (P1) and on the second row (P2) for each axle were 40% or less.

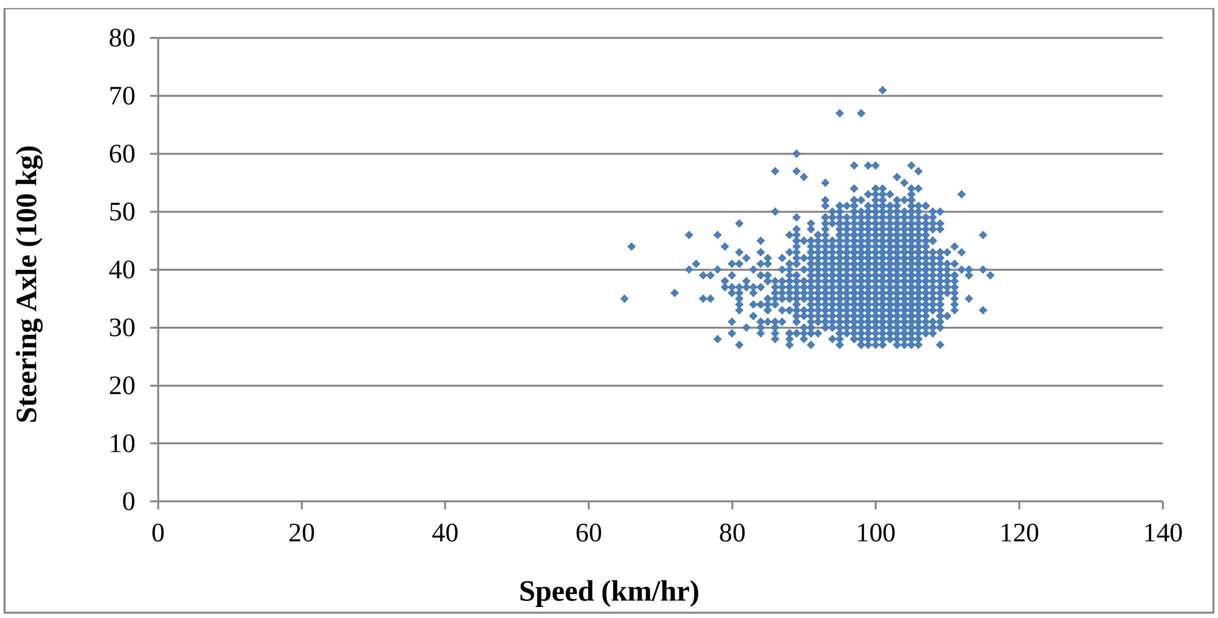


Figure 4-46- Polymer piezoelectric sensor estimates at different speeds for the Highway 401 site

- The differences between P1 and P2 estimates for GVW were 20% or less.
- Class 9 trucks have two tandem axles which are the drive and semitrailer (rear) tandem axles. The distance between axles in the semitrailer tandem axle is changeable while in the drive tandem axle it is not. In each tandem axle, the differences were 25% or less.

- Regression lines for the steering axle weights versus averages of axles in the drive and rear's tandem axles were constructed. The normal probability plot (NPP) for each relationship illustrated no severe deviation from normality. Data with 99% confidence interval (CI) were selected as for data analysis.
- A steering axle weight of less than 2.7 tons and more than 4.6 T were eliminated since there is less data in this range.
- Less than 2% of the data were eliminated by the data preparation procedure and 7238 data points for November 5 to 11 inclusive 2010 were ready for analyses.

4.3.10 Summary of the Analysis of Data from the Highway 401 Site

The preliminary analysis of piezoelectric WIM sensors data at the Highway 401 site can be summarized as follows:

1. The quartz polymer sensing system's electronic require more adjustments for producing speed and accurate weight estimations.
2. The polymer piezoelectric sensor is observed to have the following behaviours:
    a. Increases in the steering axle load will result in wider distribution of estimated axle loads in trucks' and semitrailers' axles. The signal to noise ratio remains roughly constant over weight ranges however, which is useful knowledge.
    b. Most of the data are in the range of speeds from 90 to 110 km/hr. At the current time, it is impossible to report the effect of speed on the weight estimation of the polymer piezoelectric sensors based on the Highway 401 site. Since the sensors were calibrated in the speed range of 98 to 102 km/hr, it may be inferred that the speed range of 95 to 105 km/hr has the most reliable data for analysis,
    c. Changes in weight estimations can be observed with changes in air temperature specifically at temperatures higher than the calibration temperature, which was 6^{o}C. However in some months, pavement temperature may not move in the same direction as air temperature over short period of time (e.g. one hour) because of the complex physics and heat masses of the layers of base and pavement materials, moisture and air temperature. Typically this happens in the fall or spring with air temperature ranges of 5^{o}C to 20^{o}C. A better relationship of air temperature with error was observed than of pavement temperature with error.
3. The GVW load spectra illustrate the proper placement of unloaded trucks. Recalibration of polymer piezoelectric using the auto-calibration feature of the WIM system and more data

collection in the future are recommended in order to precisely updating the GVW and axle load spectra over the pavement.

4.4 Effect of Pavement Temperature on Polymer Piezoelectric Sensors under Highway 401 Site Typical Traffic Stream

The effect of air temperature was investigated on the polymer piezoelectric sensors' estimations under traffic stream at the Highway 401 site. Based on a data acquisition opportunity that occurred later in the study unloaded and loaded trucks were separated to have a better understanding of how pavement temperature influences the estimation accuracy of polymer piezoelectric sensors.

4.4.1 Effect of Pavement Temperature on All Weight Classes

The following models were constructed using pavement temperature using the March 2011data at the highway 401 site, since after installation of the temperature sensor in October 2010, the pavement temperature data was available from January 2011. Figure 4-47 illustrates the effect of temperature on the polymer piezoelectric sensors' output for all data combined. The effect of temperature on the sensors' output for loaded and unloaded truck data sets can be shown in Figure 4-48 and Figure 4-49. It seems that with increase in weight class of trucks, the effect of temperature on the sensors' output will increase.

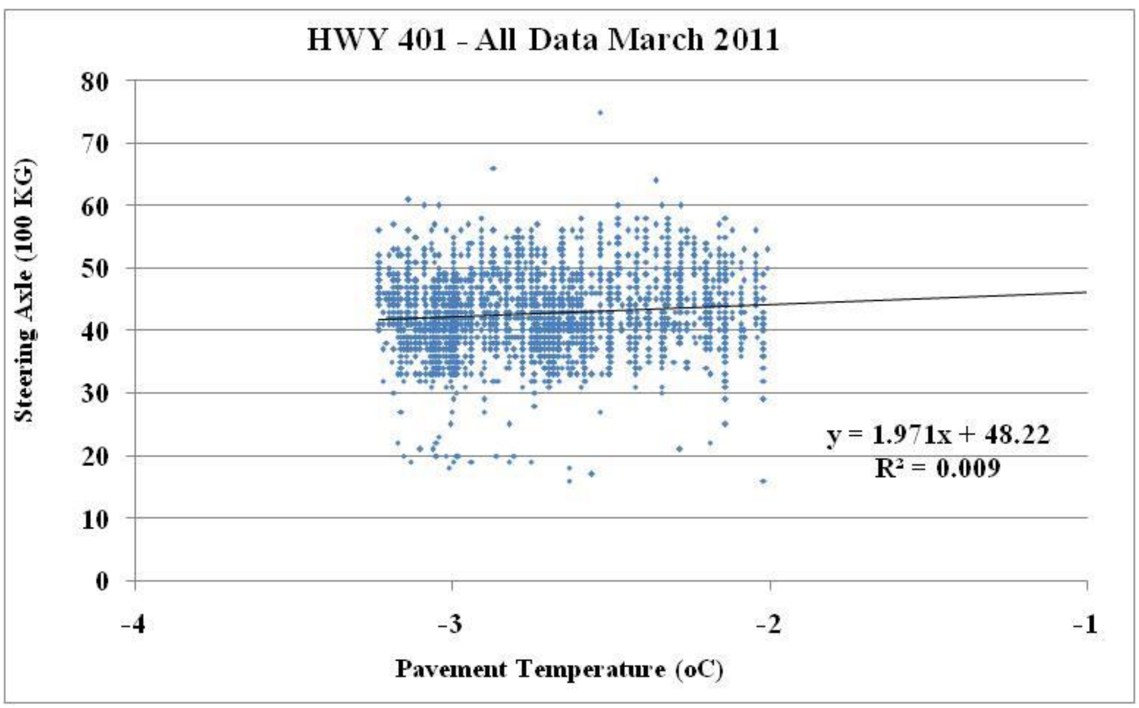


Figure 4-47- Effect of cold pavement temperatures on polymer piezoelectric sensor's estimation at the Highway 401 site

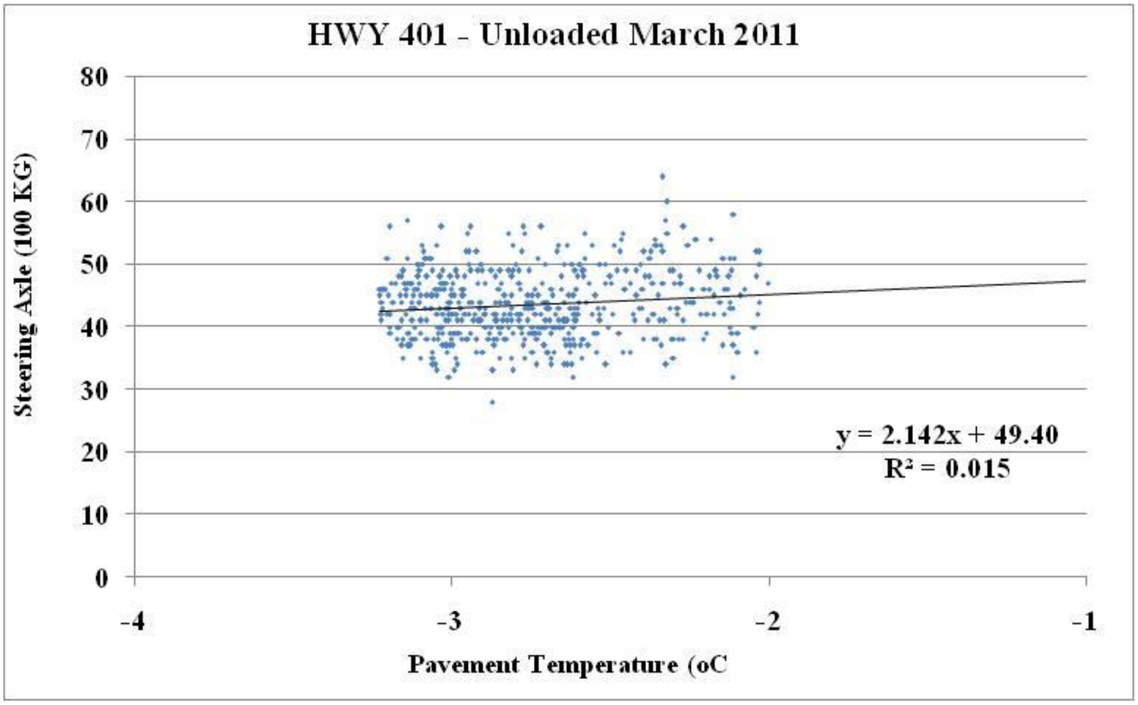


Figure 4-48- Effect of cold pavement temperatures on polymer piezoelectric sensor's estimations for unloaded trucks at the Highway 401 site

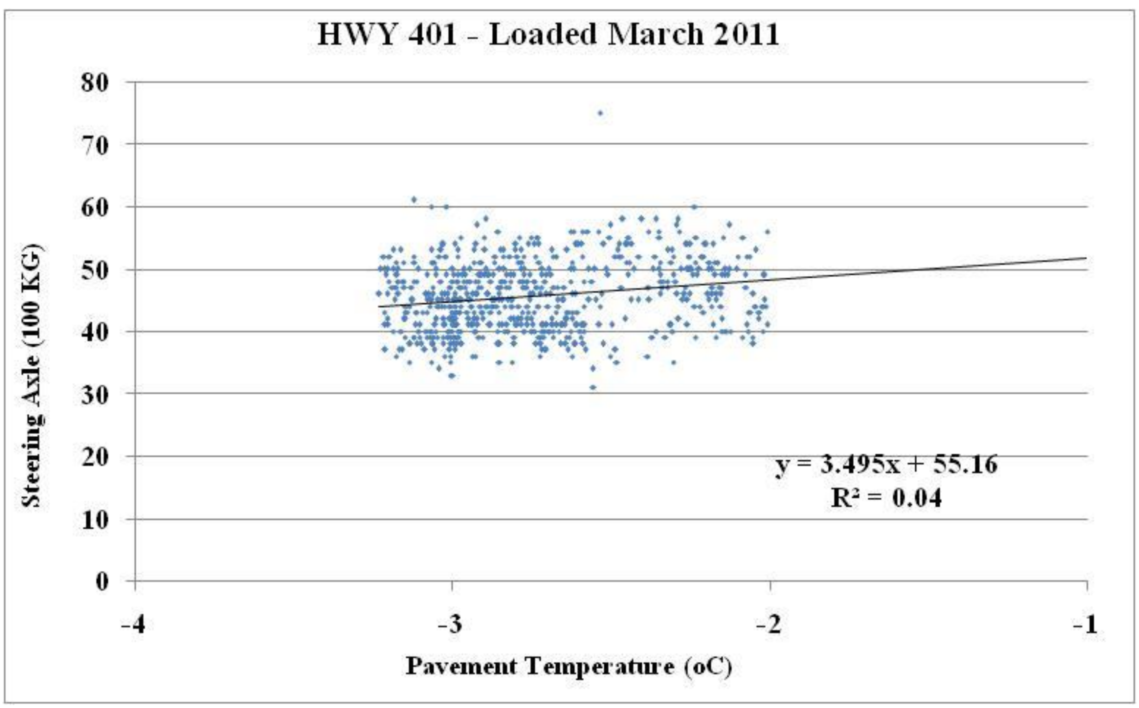


Figure 4-49- Effect of cold pavement temperatures on polymer piezoelectric sensor's estimations for loaded trucks at the Highway 401 site

Chapter 5
Summary and Conclusions

5.1 Research Summary

This research study focused on gaining knowledge and experience concerning the behavior of piezoelectric weigh-in-motion sensing systems by installing three types of piezoelectric WIM sensors in two types of roads with different load and traffic conditions. Each site experienced the same cold climate conditions of southern Ontario and data selected for analyses are from the first year of installations for both sites, in which the pavements were in their best condition. The main differences in experimental conditions for the two sites are summarized, before stating the conclusions of this thesis.

At the Landfill site, the following conditions were observed:

- Traffic is very dependent upon the business hours of the Waste Management facility at the Region of Waterloo, therefore there is no traffic at night,
- The load conditions over this site change seasonally, with maximum loads in mid-summer, and minimum loads in mid-winter time,
- The posted maximum speed at the site is 40 km/hr; however, the observed average speed at the landfill is 50 to 60 km/hr,
- The volume of vehicles over the site was between 150 to 300 vehicles per day in all classes during the period of this study,
- The most frequent vehicles at the landfill are the class 6 garbage trucks. There are few class 9 or 10 vehicles as well, and
- Almost all of the trucks over the WIM station at the landfill southbound were loaded.

At the Highway 401 site, the following conditions were observed:

- There is intensive 24 hour traffic at the site in all seasons,
- It is not expected that the load spectra over this site experiences significant changes seasonally, according to the previous studies and expert knowledge,
- Speeds of trucks are typically in the range of 90 to 110 km/hr, depending on the trucks' loads and road conditions. The site does not experience significant congestion,
- The characteristic vehicle at the Highway 401 site is the class 9, 3S2 truck. There are fewer class 6 or 7 vehicles at this site,
- The volume of all vehicles and the FHWA class 9 trucks over the site are typically in the range of 4,500 to 9,000 and 1800 to 3600 per day respectively, and

- Not all of the trucks that pass over the WIM station at the Highway 401 site are fully loaded, but most are.

5.2 Conclusion

Considering these conditions and the analyses presented in the previous chapters the main conclusions of this thesis are:

1) Understanding that piezoelectric sensors are designed for highway traffic and for high speeds, the factorial experiment method was used for the data from the Landfill site, where there is lower speed traffic. This method confirmed that lower speeds significantly affect all sensor systems' estimation accuracies, specifically at speeds lower than 50 km/hr.
2) Based on the experiments conducted at both sites, it can be concluded that temperature and transverse location of axle load over the sensors are the first two most significant factors (comparing to weight range and speed) affecting the polymer and ceramic piezoelectric sensors, specifically in warmer months e.g. June to October in southern Ontario. The interaction effects of the temperature and transverse location of axle load over the sensors is also strongly significant for polymer and ceramic piezoelectric sensors.
3) It was observed that during winter in southern Ontario, during which the air temperature may decrease to -20^{o}C, the pavement temperature will not decrease further than -5^{o}C and the effect of air temperature on the sensor's performance is thus less significant for the air temperature range of -5^{o}C to -20^{o}C.
4) It was also found that the best weather conditions for manual calibration of piezoelectric WIM sensors for experimentation are during dry weather with air temperatures close to 30 (mid-summer) to 5 (mid-fall) degrees Celsius, when the effect of temperature falling (summer to fall and fall to winter) can be learned and thus used for future compensation procedures.
5) The impact of air temperature can be modeled with simple functions using regression analysis, and these models can potentially be used to compensate raw sensor output or in auto-calibration algorithms.
6) The effect of weight was not investigated by the factorial experiment method; however, analyses of the data from the Highway 401 site showed sensitivity with respect to error over the weight ranges for the polymer piezoelectric sensors.
7) Analyses of the polymer, quartz and ceramic piezoelectric sensors data from the landfill site in the period from July to October 2008 (in the period of the first 6 months after calibration of the sensors) showed that all the sensor systems' estimation accuracies were affected by the weight factor at least to some extent.

8) The analysis of residuals for the polymer piezoelectric sensors for the Landfill data shows that residuals are not normally distributed (the mean of residuals is not zero and the scatter pattern of residuals show that the variance is not constant), which means that a linear regression model is not adequate for modeling the weight data. The polymer piezoelectric sensor seems to be significantly affected by increasing the weight class.
9) Transformation of parameters using the Box and Cox transformation method was applied to deal with the issue of not constant error variance of the polymer piezoelectric sensors' estimation accuracy. The maximum likelihood estimate for λ, which minimizes the residual sum of squares of observations are 0.048 for the sensor estimations and 0.012 for the static weights. Since both lambdas are very close to zero, it can be concluded that a reasonable transformation for estimated and static weights is a logarithmic transformation.

5.3 Contributions

This thesis has two major areas of contributions: (1) contribution to the transportation industry, and (2) contribution to the body of knowledge of piezoelectric weigh-in-motion sensing in civil engineering. A brief discussion on these areas of contribution follows.

1. This research study facilitated improved deployment of the studied weigh-in-motion technologies through presenting benefits in terms of sensor performance in different pavement designs, calibration time reduction procedures, and by increasing the potential benefits of selecting the least expensive polymer technology for use in the transportation industry. This work also represented a strong academic-industry partnership and knowledge transfer to industry, and
2. This thesis enriched the body of knowledge in the area of piezoelectric sensors' sensitivity to the climate and road conditions in traffic engineering by: (a) investigating the effects of factors including air temperature, speed of vehicle and transverse location of vehicle on road, and finding the most influential factor, (b) modeling the polymer piezoelectric sensor's estimation error against air and pavement temperature, and (c) modeling the polymer piezoelectric sensor's estimation against the weight factor by finding the best transformation for the estimated weight of trucks for this type of sensor.

5.4 Limitations

The limitations of this research study are as follows:

1. Although temperature affects the estimation of the polymer piezoelectric sensors significantly, there is complexity in finding the best relationship between temperature and the sensors' output specifically for the mid-spring (mid-April to mid-May) and mid-fall (mid-November to mid-

December) periods. Since sensors have been surrounded by a specific epoxy grout, sensors' pattern of temperature change does not follow the same rule as asphalt does, specifically when pavement temperature changes so quickly such as in mid-spring and mid-fall periods. It is observed that in this situation, the sensors' estimation pattern of change more follows the air than pavement temperature. Therefore, the pattern of temperature change at the place of installation should be known to avoid leading to an unexpected result.

2. The pavement structures are not significantly different at both experimental sites; however, there are three lanes plus a paved shoulder at the Highway 401 site on eastbound versus one lane and no paved shoulder at the Landfill site on southbound. The impacts of the pavement design at the sites on the estimation of piezoelectric sensors were assumed to be consistent; however, this hypothesis requires additional work to be proven.
3. The piezoelectric WIM sensors at both sites were calibrated periodically using a two-axle CPATT van with a total weight of 3 tons and axle weights between 1.2 to 1.6 tons. The calibration approach was driven by financial constraints, but the most widely accepted calibration approach is to use the characteristic vehicle at each site to calibrate the sensors. However, practical experience over effects of weight factor on the piezoelectric sensors' output was gained. A manual calibration procedure using Excel® sheets for all types of sensors has also been developed.

5.5 Future Work

This thesis investigated the impact of climate and traffic conditions on the output of polymer piezoelectric WIM sensors, particularly the effects of temperature and weight. A number of recommendations concerning future research are listed below:

Deepen and broaden the experimental results by conducting more analysis for investigating the impact of:

- weight factor on the estimation of piezoelectric sensors (all types) at the landfill site by extracting "lighter trucks" and "heavier trucks" data and conduct the analysis to capture possible changes in sensors' output in different vehicle weight classes, and
- air temperature on typical traffic in the landfill site on all types of piezoelectric sensors using the factorial experiment method.

The results of this complementary research has potential application to

1. Construct a two-dimensional bin-based compensation algorithm for weight estimation, specifically for the polymer piezoelectric sensors. The results can be validated using the characteristic pre-weighed vehicles in both sites, and
2. Develop possible methods for tracking a malfunctioning sensor in a system.

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Appendix A
Roughness and IRI Measurements and WIM Installation Details at the Landfill Site

A.1. Measurement of Roughness at the Landfill Site

According to ASTM (ASTM E 867 2006, p. 1052), the term “Traveled Surface Roughness” is defined as: “The deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage, for example, longitudinal profile, transverse profile, and cross slope”. In addition, the term “True International Roughness Index” is defined as: “The value of international roughness index that would be computed for a longitudinal profile measurement with the constant interval approaching zero”

The research team chose International Roughness Index (IRI), to quantify the measured profile of the test track at the Landfill site measured by rod and level method. ASTM (ASTM E1364 1995 (Reapproved 2005), p. 1112) determined the max interval between measuring points as 305 mm (1 ft) class 1 (0.5 to 1 mm resolution, IRI between 1 and 5 m/km) and 610 mm (2 ft) class 2 (1 to 2 mm resolution, IRI between 1 and 5 m/km). A 300 mm base interval as used for measuring road roughness in class 1. Direct calculation of IRI requires surveying the longitudinal profile of a wheel track, since IRI is a characteristic of the road profile (Sayers, Gillespie & Paterson 1986). Figure A. 1 shows road classifications with different IRI ranges.

A.1.1. Roughness and IRI

The first measurements for roughness and IRI on the Landfill performed in June 2007, approximately three and half months before WIM installation. The results of this dynamic survey over the WIM test track are displayed in Table A. 1.

Table A. 1- Left and right IRI and MRI resulted from the dynamic survey (seven runs at four speeds including 30, 40, 50 and 60 km/hr) over the site

The Average Left IRI (m/km)	The Average Right IRI (m/km)	The Average MRI (m/km)
2.92	**3.37**	**3.15**

In November 2007 the research team performed the conventional survey according to ASTM (ASTM E1364 1995 (Reapproved 2005)) using an optical level and rod for 450 to 500 spots per wheel path line (0.3m interval). Figure A. 2 shows the site layout and locations of longitudinal and transverse profiles. The elevation points and longitudinal profile of the test site prepared by Profile Viewing and AnaLysis (ProVAL, ver. 2.7) illustrated in Figure A. 3 and Figure A. 4.

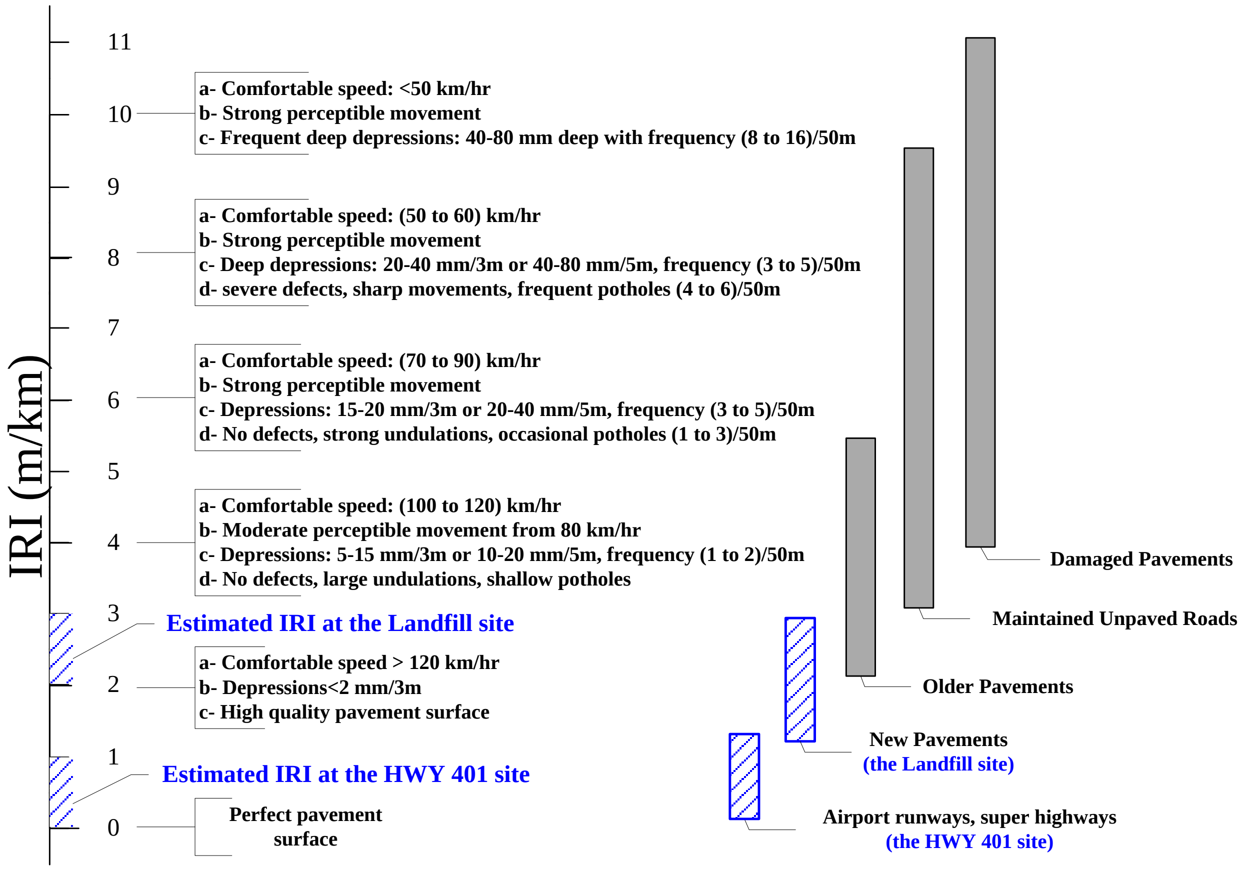


Figure A. 1- Road roughness estimation scale for paved roads with asphaltic concrete or surface treatment (Chipseal) and unpaved roads (ASTM E1926 1998 (Reapproved 2003), p. 1198), (Sayers, Karamihhas 1998, p. 48)

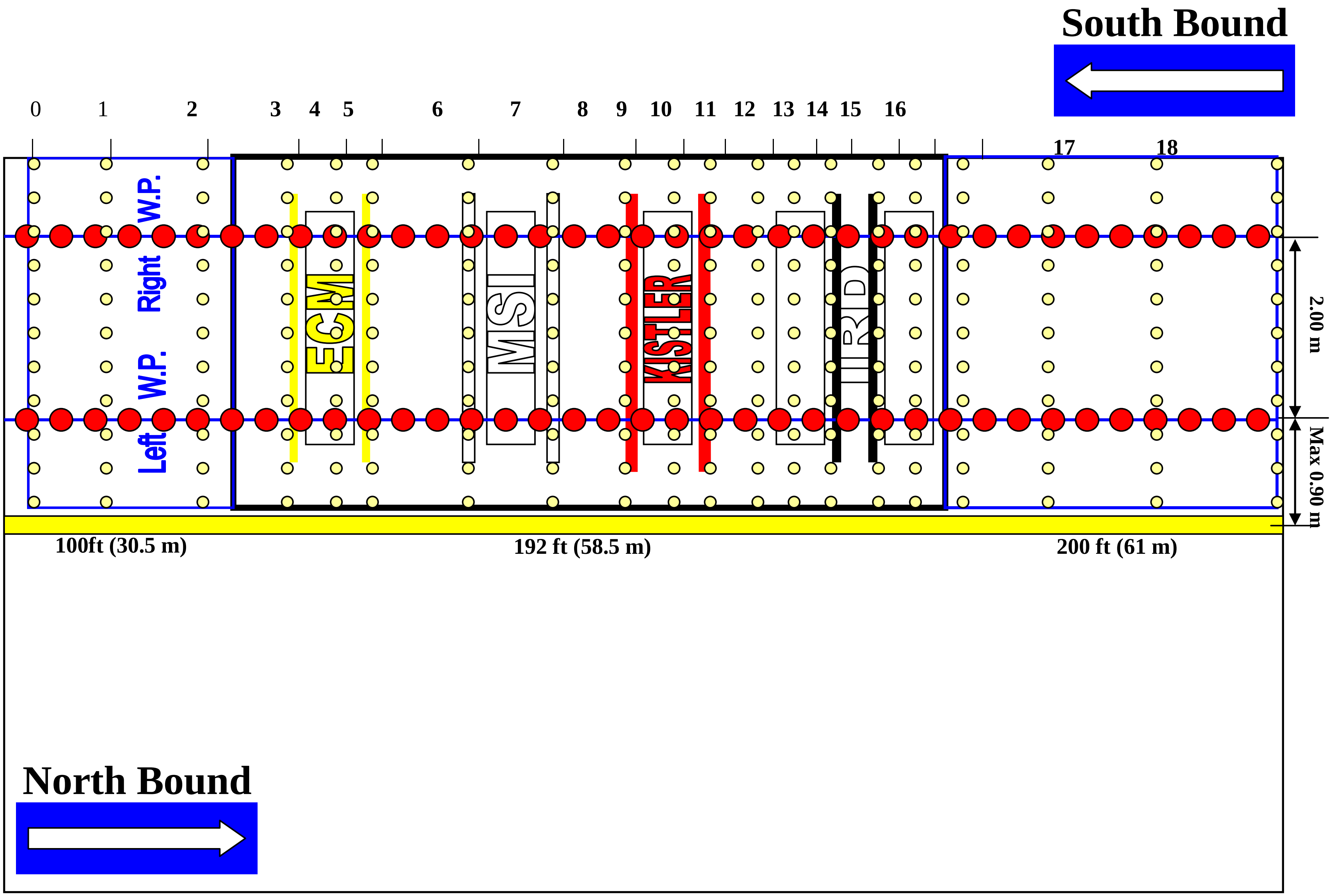


Figure A. 2- The landfill site layout for longitudinal and transverse profile measurement

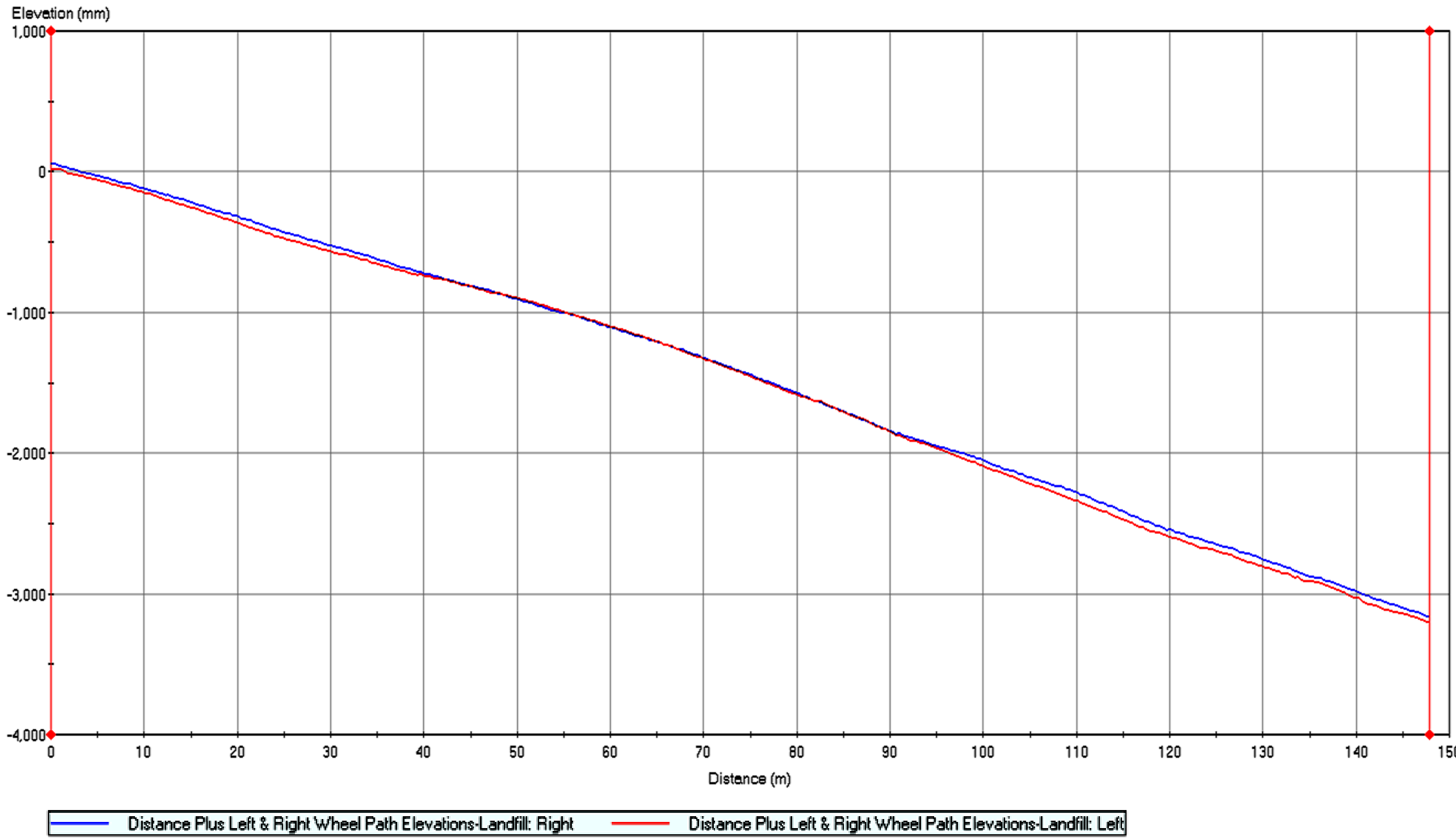


Figure A. 3- The elevation points on internal and external wheel paths by ProVAL 2.73 (the Landfill on southbound lane –Nov. 2007) (The Transtec Group 2008, ProVAL)

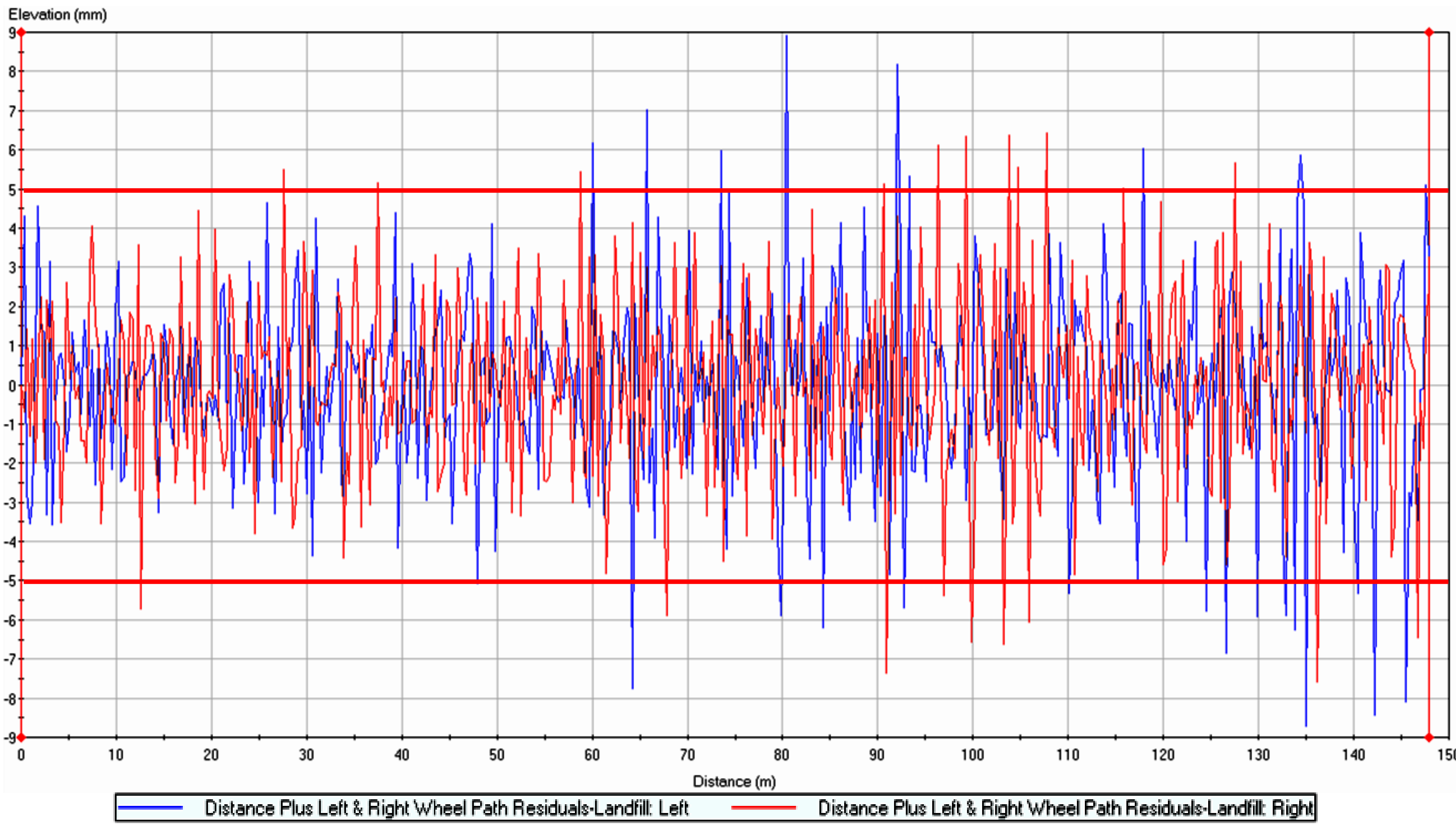


Figure A. 4- Longitudinal profile on internal and external wheel paths by ProVAL 2.73 (Landfill on the SB lane-Nov. 2007) (The Transtec Group 2008, ProVAL)

A.1.2. IRI Estimation

The estimation of IRI by subjective methods requires engineering judgments, longitudinal profile and expert observations of the site along with guidelines and standards. To gain a reasonable IRI, the following steps were carried out to estimate IRI of WIM site at the Landfill:

- Drew the true planar lines, which can best represent each wheel path of southbound lane, using SLOPE() and INTERCEPT() functions of Microsoft Excel
- Subtracted each point of the new line from the corresponding point in the wheel path line. This will produce the residual for each point.
- Investigated the residuals for the period of ten points (three meters) to determine the frequency of more than 5 mm values. According to Figure A. 1, the deflections between 5 and 15 mm per 3 meters, 10 and 20 mm per 5 meters (with frequency of 2-1 per 50 m) or many shallow deflections on the surface describes the IRI between 3 and 5.
- Interpreted and categorized the deflection on wheel paths at 50 m interval (Figure A. 1):
    - Deflections per 3 m categorized into 3 fractions: (5-9), (10-12) and (12-15) mm
    - At the time, the deflections at WIM site demonstrated the fraction (5-9) mm
    - The frequency of the fraction (5-9) mm in each 50 meters categorized into five fractions and the estimated IRI determined as follow:
        - –Frequency of zero to five, IRI estimated for (2.5-3.0) m/km
        - –Frequency of five to ten, IRI estimated for (3.0-3.5) m/km
        - –Frequency of ten to fifteen, IRI estimated for (3.5-4.0) m/km
        - –Frequency of fifteen to twenty, IRI estimated for (4.0-4.5) m/km
        - –Frequency of twenty to twenty five, IRI estimated for (4.5-5.0) m/km

Table A. 2 demonstrates the results of this interpretation. This interpretation was supported by the researchers' static and dynamic observations of the site. Table A. 3 averages the external and internal wheel paths' IRI and demonstrates the MRI for the southbound lane at WIM site.

A.1.3. Conclusion

According to Table A. 1 for dynamic IRI analysis in June 2007 and results of IRI estimation on longitudinal survey in November 2007, it is concluded that during a 5-month period from June to November 2007, no significant changes happened to the IRI of the road. Additionally, it confirms that the pavement is in an acceptable condition with the IRI between (2 to 3) m/km. The study shows the pavement is still in the block of "new pavements"; however, it warns that the pavement is experiencing some minor "surface imperfections" (Figure A. 2).

Table A. 2- The frequency of (5-9) mm per 50 m and the estimated IRI according to Figure A. 1 (ASTM E1926 1998 (Reapproved 2003))

No.	First 50 m 5m to 9m deflections		IRI		Second 50 m 5m to 9m deflections		IRI		Third 50 m 5m to 9m deflections		IRI	
	Ex- W.P.	**In- W.P.**	**Ex - IRI**	**In- IRI**	**Ex- W.P.**	**In- W.P.**	**Ex - IRI**	**In- IRI**	**Ex- W.P.**	**In- W.P.**	**Ex - IRI**	**In- IRI**
1	5.07	5.71	2.5-3	2.5-3	6.17	5.43	3.5-4	3-3.5	5.32	6.62	3.5-4	3-3.5
2		5.49			7.77	5.88			6.04	6.38		
3		5.15			7.03	5.14			5.78	5.54		
4					5.97	7.35			6.86	6.06		
5					5.89	6.13			5.91	6.44		
6					8.92	5.37			5.88	5.02		
7					6.21	6.35			6.27	5.67		
8					8.18	6.57			5.85	7.58		
9					5.68				8.71	6.47		
10					5.32				5.32			
11									8.44			
12									8.10			
13									5.10			

W.P. = Wheel Path Ex = External In = Internal

Then, the resulted averages of IRI for each wheel path and the MRI for the lane are displayed in Table A. 3:

Table A. 3- The average estimated IRI for each wheel path and the total IRI estimated for each wheel path at test (November 2007)

No.	First 50 m IRI (m/km)		MRI (m/km)	Second 50 m IRI (m/km)		MRI (m/km)	Third 50 m IRI (m/km)		MRI (m/km)	WIM Site IRI (m/km)		MRI (m/km)
	Ex - IRI	**In- IRI**		**Ex - IRI**	**In- IRI**		**Ex - IRI**	**In- IRI**		**Ex - IRI**	**In- IRI**	
1	2.75	2.75	2.75	3.75	3.25	3.50	3.75	3.25	3.50	3.42	3.08	3.25

A.2. WIM Installation Details

Table A. 4- WIM installation workforce at the Landfill site (starting time: 7:00am, ending time: 6:00 pm)

Name	Sep. 21, 07	Sep. 22, 07	Sep. 23, 07	Sep. 24, 07	Sep. 25, 07	Sep. 26, 07	Sep. 27, 07	Sep. 28, 07	Oct. 09, 07	Nov. 2, 07	Nov. 27, 07	Nov. 28, 07	Total
Fariba Amiri*	6:30$_{am}$-9:30^{pm}	6:30$_{am}$-8:30^{pm}	5:00^{pm}-7:00^{pm}	-	-	-	-	-	-	-	11:00$_{am}$-5:00^{pm}	-	37
Carl Haas	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	-	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-11:00$_{am}$	1:00^{pm}-3:00^{pm}	9:00$_{am}$-11:00$_{am}$	-	-	-	63
Doug Hirst*	-	-	-	-	-	4:00^{pm}-6:00^{pm}	9:00$_{am}$-1:00^{pm}	-	-	-	-	-	6
Edward Jiang	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	-	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:30^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	11:00$_{am}$-4:30^{pm}	11:00$_{am}$-4:30^{pm}	110.5
Gerhard Kennepohl	-	-	-	-	10:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	-	1:00^{pm}-2:00^{pm}	-	-	-	-	20
Antonio Marcon*	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	-	1:00^{pm}-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	-	-	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	200^{pm}-5:00^{pm}	-	74
Hassan Nasir	-	-	-	-	-	-	-	-	-	11:00$_{am}$-1:00^{pm}	-	-	2
Saiedeh Razavi*	7:00$_{am}$-6:00^{pm}	-	-	-	-	-	-	-	-	-	-	-	11
Terry Ridgway	-	-	-	-	-	-	-	-	-	12:00^{pm}6:00^{pm}	11:00$_{am}$-5:00^{pm}	-	12
Arash Shahi*	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-1:00^{pm}	-	-	-	-	-	-	-	-	-	-	17
Taraneh Shahi*	-	7:00$_{am}$-1:00^{pm}	-	-	-	-	-	-	-	-	-	-	6
Richard K.C. To	-	7:00$_{am}$-6:00^{pm}	-	-	-	-	-	-	-	-	-	-	11
Shahram H. Vaziri	6:30$_{am}$-9:30^{pm}	6:30$_{am}$-8:30^{pm}	5:00^{pm}-7:30^{pm}	6:30$_{am}$-7:30^{pm}	6:30$_{am}$-9:30^{pm}	6:30$_{am}$-7:30^{pm}	6:30$_{am}$-8:30^{pm}	6:30$_{am}$-9:30^{pm}	7:00$_{am}$-7:00^{pm}	7:00$_{am}$-7:00^{pm}	11:00$_{am}$-8:30^{pm}	11:00$_{am}$-7:30^{pm}	143.5
Ron White	-	7:00$_{am}$-6:00^{pm}	5:00^{pm}-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-3:00^{pm}	-	-	-	-	-	53
Duncan Young*	-	7:00$_{am}$-6:00^{pm}	-	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-6:00^{pm}	7:00$_{am}$-1:00^{pm}	-	7:00$_{am}$-6:00^{pm}	-	-	-	61
Alanna Zhang*	-	7:00$_{am}$-6:00^{pm}	-	-	-	-	-	-	-	-	-	-	11
Total Hours	85	117	5.5	62	78	81.5	47	29	47	42	30	14	**638**

*Volunteers

Table A. 5- Schedule of the work (starting time: 7:00am, ending time: 6:00 pm)

No.	Task	Fri. 21st	Sat. 22nd	Sun. 23rd	Mon. 24th	Tues. 25th	Wed. 26th	Thu.27th	Fri. 28th	Mon. Oct. 09	Fri. Nov. 02	Tue. Nov. 27	Wed. Nov. 28
1	Traffic Control	•	•		•	•				•	•	•	
2	Weed cut	•		Holiday									
3	Line Draw & Place Different Sensor Locations	•											
4	Trench Work	•	•		•								
5	Quartz piezoelectric cuts	•	•										
6	Polymer piezoelectric cuts		•		•								
7	Ceramic piezoelectric cuts	•	•										
8	Loop cuts and Wire cuts				•	•							
9	Quartz piezoelectric Installation				•								
10	Quartz piezoelectric Grind and Belt Sand Work				•	•				•			
11	Polymer piezoelectric Installation				•								
12	Ceramic piezoelectric Installation		•										
13	Loop Installation					•							
14	Wire Cuts Grout					•							
15	Conduit Work (Pipe cuts, install and glue)						•						
16	Cable work (from the junction box 3 to the Cabinet)						•	•					
17	Connections to the Cabinet & Final Tests							•					
18	Backfill (sand plus in-situ backfill material)							•	•	•			
19	Insulation of Wires and Conduit								•	•			
20	Cleaning the Site								•	•			
21	Completion of Grouting (Including the wrong cuts)									•			•
22	Film & Photograph the Installation Steps		•		•	•	•	•	•	•		•	•
23	Survey (Longitudinal & Transverse Profiles & As-Built)										•	•	
24	Paint and Flag the Trenches' Pathway										•	•	•
25	Pre-Calibration												•

Appendix B

Performance Comparisons by the Factorial Experiment Method

Table B. 1–The quartz sensor data arrangements for the temperature experiment

			Speed (Factor B, j=1,2)	
			43 km/hr	**45 km/hr**
Quartz Sensor*	**Air Temperature (Factor A, i=1,…,5)**	**"(8.00 to 9.99) ^{o}C"**	2766.9 2676.2 2449.4	2630.8 2676.2 2540.1
		"(10.00 to 11.99) oC"	2585.5 2585.5 2585.5	2585.5 2630.8 2449.4
		"(12.00 to 13.99) ^{o}C"	2585.5 2630.8 2540.1	2585.5 2766.9 2540.1
		"(14.00 to 15.99) oC"	2585.5 2676.2 2766.9	2630.8 2721.6 2903.0
		"(16.00 to 17.99) oC"	2494.8 2630.8 2540.1	2540.1 2766.9 2540.1

*The three values at the factor levels are sensor estimations of the static GVW of the CPATT van (2800 kg)

Table B. 2– The polymer sensor data arrangements for the temperature experiment

			Speed (Factor B, j=1,2)	
			43 km/hr	**45 km/hr**
Polymer Sensor	**Air Temperature (Factor A, i=1,…,5)**	**"(8.00 to 9.99) ^{o}C"**	1995.8 2086.5 2268.0	2041.2 2041.2 2222.6
		"(10.00 to 11.99) oC"	2585.5 2857.6 2903.0	2404.0 2766.9 2540.1
		"(12.00 to 13.99) ^{o}C"	2812.3 2812.3 3084.4	2766.9 3039.1 3220.5
		"(14.00 to 15.99) oC"	3311.2 3039.1 3311.2	3311.2 2993.7 3175.1
		"(16.00 to 17.99) oC"	3175.1 2857.6 2857.6	3039.1 2948.4 2721.6

Table B. 3– The ceramic sensor data arrangements for the temperature experiment

			Speed (Factor B, j=1,2)	
			43 km/hr	**45 km/hr**
Ceramic Sensor	**Air Temperature (Factor A, i=1,…,5)**	**"(8.00 to 9.99) ^{o}C"**	1179.3 1179.3 1134.0	952.5 1179.3 1179.3
		"(10.00 to 11.99) oC"	1224.7 1859.7 2222.6	1360.8 1995.8 1859.7
		"(12.00 to 13.99) ^{o}C"	2766.9 2721.6 2449.4	2494.8 2857.6 2449.4
		"(14.00 to 15.99) oC"	2903.0 3220.5 3356.6	2903.0 3220.5 3265.9
		"(16.00 to 17.99) oC"	2903.0 3039.1 3039.1	3175.1 3175.1 3084.4

Table B. 4– The quartz sensor data arrangements for the path run experiment

			Path Run (Factor B, j=1,2,3)		
			path run 1 (n= 1,2,3,4)	**path run 2 (n= 1,2,3,4)**	**path run 3 (n= 1,2,3,4)**
Quartz Sensor*	**Air Temperature (Factor A, i=1,2)**	**"(-10.99 to -9.50) oC"**	2086.5 2041.2 2086.5 2313.3	2721.6 2676.2 2676.2 2721.6	2676.2 2676.2 2630.8 2585.5
		"(-9.49 to -8.00) oC "	2131.9 2086.5 2131.9 1995.8	2721.6 2721.6 2676.2 2766.9	2676.2 2766.9 2630.8 2630.8

*The four values at the factor levels are sensor estimations of the static GVW of the CPATT van (2800 kg)

Table B. 5- ANOVA for air temperature and path run effects on the quartz sensors

Source of Variation	S of S	df	MS	f_0	P-Value	Significancy
Temperature, A	85.7	1	85.7	0.02	>0.25	
Run, B	1776788.5	2	888394.2	195.53	<<0.01	**Very Strongly Significant**
AB	7372.6	2	3686.3	0.81	>0.25	
Error	81784.1	18	4543.6			
Total	1866030.8	23				

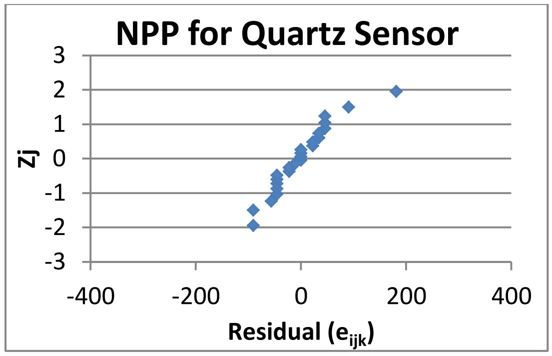


Figure B. 1- Plot of the quartz sensor's residuals for the air temperature and path run factors

Table B. 6– The polymer sensor data arrangements for the path run experiment

			Path Run (Factor B, j=1,2,3)		
			path run 1 (n= 1,2,3,4)	**path run 2 (n= 1,2,3,4)**	**path run 3 (n= 1,2,3,4)**
Polymer Sensor	**Air Temperature (Factor A, i=1,2)**	**"(-10.99 to -9.50) °C"**	2585.5 2585.5 2676.2 2540.1	2358.7 2404.0 2404.0 2358.7	2494.8 2540.1 2585.5 2449.4
		"(-9.49 to -8.00) °C "	2630.8 2585.5 2676.2 2358.7	2540.1 2630.8 2585.5 2540.1	2585.5 2494.8 2449.4 2494.8

Table B. 7- ANOVA for air temperature and path run effects on the polymer sensors

Source of Variation	**S of S***	**Df****	**MS*****	**f_0**	**P-Value**	**Significancy**
Temperature, A	14488.0	1	14488.0	2.68	0.1<P<0.25	Very Weak
Run, B	43206.7	2	21603.3	4.00	0.025<P<0.05	**Moderately Significant**
AB	62409.6	2	31204.8	5.78	0.025<P<0.01	**Strongly Significant**
Error	97215.0	18	5400.8			
Total	217319.3	23				

*Sum of Square

**Degree of Freedom

***Mean of Sum of Square

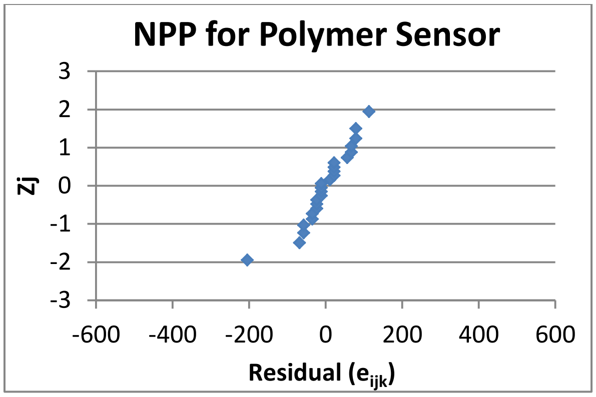


Figure B. 2- Plot of the polymer sensor's residuals for the air temperature and path run factors

Table B. 8– The ceramic sensor data arrangements for the path run experiment

			Path Run (Factor B, j=1,2,3)		
			path run 1 (n= 1,2,3,4)	**path run 2 (n= 1,2,3,4)**	**path run 3 (n= 1,2,3,4)**
Ceramic Sensor	**Air Temperature (Factor A, i=1,2)**	**"(-10.99 to -9.50) oC"**	2766.9 2676.2 2676.2 2812.3	3764.8 3628.7 3810.2 3810.2	2766.9 3039.1 2948.4 2766.9
		"(-9.49 to -8.00) oC "	2812.3 2812.3 2812.3 2993.7	4037.0 3900.9 4218.4 4127.7	2948.4 2494.8 2358.7 2857.6

Table B. 9- ANOVA for air temperature and path run effects on the ceramic sensors

Source of Variation	S of S	df	MS	f_0	P-Value	Significancy
Temperature, A	34291.0	1	34291.0	1.50	0.1<P<0.25	Very Weak
Run, B	6791848.2	2	3395924.1	148.55	<<0.01	**Very Strongly Significant**
AB	291302.1	2	145651.0	6.37	<0.01	**Very Strongly Significant**
Error	411492.1	18	22860.7			
Total	7528933.4	23				

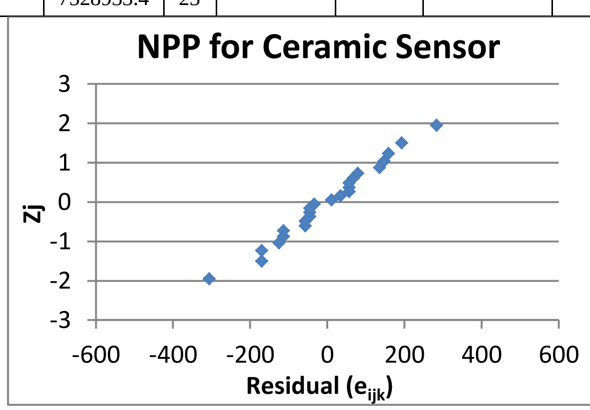


Figure B. 3- Plot of the ceramic sensor's residuals for the air temperature and path run factors

Table B. 10– The quartz sensor data arrangements for the speed experiment on March 03, 2009

			Speed (Factor B, j=1,2,3)		
			30km/hr (n= 1,2,3)	50km/hr (n= 1,2,3)	70km/hr (n= 1,2,3)
Quartz Sensor*	Air Temp. (Factor A, i=1,2)	"(-7.00 to -6.50) ^{o}C"	2086.5 2086.5 2041.2	2630.8 2449.4 2585.5	2676.2 2721.6 2676.2
		"(-7.50 to -7.00) oC"	2222.6 2086.5 2268.0	2585.5 2676.2 2721.6	2721.6 2721.6 2585.5

Table B. 11- ANOVA for air temperature and speed effects on the quartz sensors, Mar. 3, 2009

Source of Variation	S of S	df	MS	f_0	P-Value	Significancy
Temperature, A	22403.5	1	22403.5	4.45	0.05<P<0.1	Weak
Speed, B	1074222.9	2	537111.5	106.80	<<0.01	Very Strongly Significant
AB	16688.3	2	8344.1	1.66	0.1<P<0.25	Very Weak
Error	60352.2	12	5029.3			
Total	1173666.8	17				

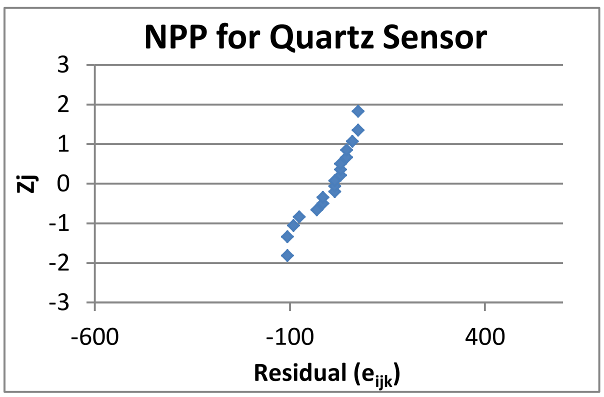


Figure B. 4- Plot of the quartz sensor's residuals for the air temperature and speed factors

Table B. 12– The polymer sensor data arrangements for the speed experiment on March 03, 2009

			Speed (Factor B, j=1,2,3)		
			30km/hr (n= 1,2,3)	50km/hr (n= 1,2,3)	70km/hr (n= 1,2,3)
Polymer Sensor	Air Temperature (Factor A, i=1,2)	"(-7.00 to -6.50) ^{o}C"	2177.2 2086.5 2086.5	2358.7 2404.0 2358.7	2404.0 2358.7 2404.0
		"(-7.50 to -7.00) oC"	2313.3 2086.5 2177.2	2268.0 2313.3 2177.2	2449.4 2358.7 2313.3

Table B. 13- ANOVA for air temperature and speed effects on the polymer sensors, Mar. 3, 2009

Source of Variation	S of S	df	MS	f_0	P-Value	Significancy
Temperature, A	1829.4	1	1829.4	0.41	>0.25	
Speed, B	162545.8	2	81272.9	18.23	<0.01	**Very Strongly Significant**
AB	29030.7	2	14515.3	3.26	0.05<P<0.1	Weak
Error	53499.2	12	4458.3			
Total	246905.0	17				

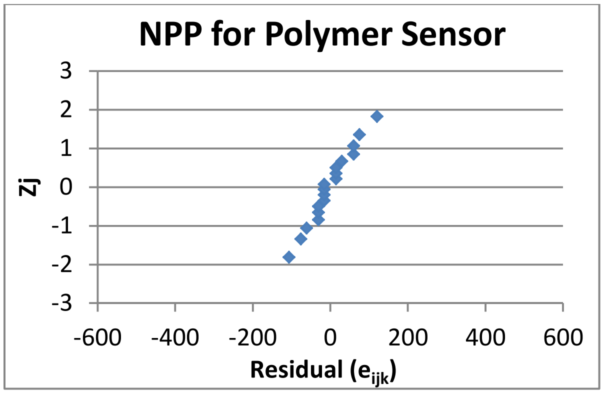


Figure B. 5- Plot of the polymer sensor's residuals for the air temperature and speed factors

Table B. 14– The ceramic sensor data arrangements for the speed experiment on March 03, 2009

			Speed (Factor B, j=1,2,3)		
			30km/hr (n= 1,2,3)	**50km/hr (n= 1,2,3)**	**70km/hr (n= 1,2,3)**
Ceramic Sensor	**Air Temperature (Factor A, i=1,2)**	**"(-7.00 to -6.50) °C"**	2449.4 2676.2 2993.7	3039.1 3175.1 2903.0	3492.7 3220.5 3583.4
		"(-7.50 to -7.00) oC"	2585.5 2404.0 2449.4	3220.5 3674.1 3175.1	3674.1 3583.4 3810.2

Table B. 15- ANOVA for air temperature and speed effects on the ceramic sensors, Mar. 3, 2009

Source of Variation	S of S	df	MS	f_0	P-Value	Significancy
Temperature, A	60468.8	1	60468.8	1.60	0.1<P<0.25	Very Weak
Speed, B	2867660.5	2	1433830.3	37.90	<<0.01	**Very Strongly Significant**
AB	267015.5	2	133507.7	3.53	0.05<P<0.1	Weak
Error	454008.6	12	37834.1			
Total	3649153.5	17				

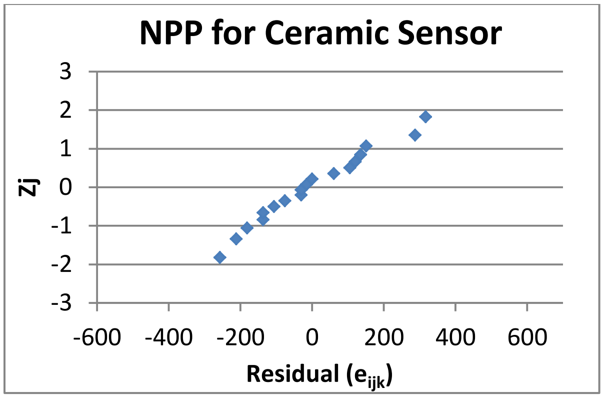


Figure B. 6- Plot of the ceramic sensor's residuals for the air temperature and speed factors

Table B. 16– The quartz sensor data arrangements for the speed experiment on March 04, 2009

			Speed (Factor B, j=1,2,3)		
			30km/hr (n= 1,..,5)	50km/hr (n= 1,..,5)	70km/hr (n= 1,..,5)
Quartz Sensor*	Air Temperature (Factor A, j=1,2)	"-0.3 to 0.0"	2540.1 2313.3 2676.2 3039.1 2585.5	2993.7 3084.4 2903.0 2948.4 2948.4	2812.3 2903.0 2766.9 2812.3 3039.1
		"-0.6 to -0.3"	3356.6 2494.8 2676.2 2903.0 2857.6	2766.9 3084.4 2948.4 2993.7 3175.1	3039.1 2812.3 2993.7 2766.9 2903.0

Table B. 17- ANOVA for air temperature and speed effects on the quartz sensors, Mar. 04, 2009

Source of Variation	S of S	df	MS	f_0	P-Value	Significancy
Temperature, A	65907.3	1	65907.3	1.74	0.1<P<0.25	Very Weak
Speed, B	291747.9	2	145873.9	3.85	0.025<P<0.05	**Moderately Significant**
AB	66798.9	2	33399.4	0.88	>0.25	
Error	909397.5	24	37891.6			
Total	1333851.6	29				

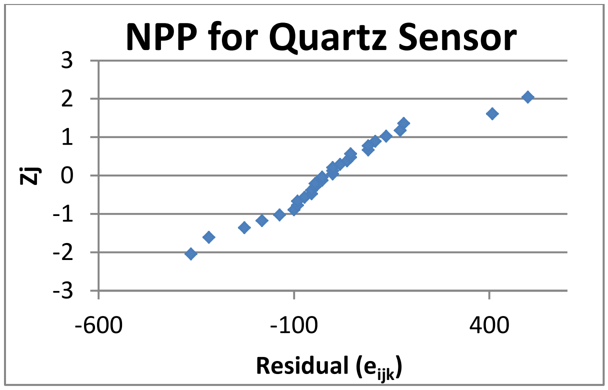


Figure B. 7- Plot of the quartz sensor's residuals for the air temperature and speed factors

Table B. 18– The polymer sensor data arrangements for the speed experiment on March 04, 2009

			Speed (Factor B, j=1,2,3)		
			30km/hr (n= 1,..,5)	50km/hr (n= 1,..,5)	70km/hr (n= 1,..,5)
Polymer Sensor	**Air Temperature (Factor A, j=1,2)**	**"-0.3 to 0.0"**	2540.1 2721.6 2903.0 2812.3 2721.6	2857.6 3129.8 2857.6 2766.9 3175.1	2857.6 3039.1 2903.0 2903.0 3175.1
		"-0.6 to -0.3"	2585.5 2540.1 2540.1 2630.8 2812.3	3084.4 3084.4 2721.6 3039.1 2857.6	2948.4 2903.0 2993.7 2903.0 3311.2

Table B. 19- ANOVA for air temperature and speed effects on the polymer sensors, Mar. 4, 2009

Source of Variation	S of S	df	MS	f_0	P-Value	Significancy
Temperature, A	5555.1	1	5555.1	0.24	>0.25	
Speed, B	586101.9	2	293050.9	12.85	<0.01	**Very Strongly Significant**
AB	32507.9	2	16253.9	0.71	>0.25	
Error	547284.5	24	22803.5			
Total	1171449.4	29				

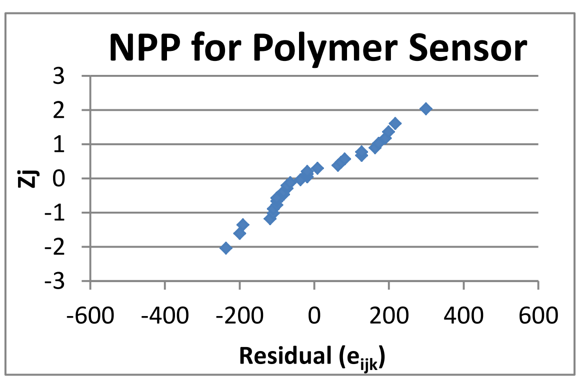


Figure B. 8- Plot of the polymer sensor's residuals for the air temperature and speed factors

Table B. 20– The ceramic sensor data arrangements for the speed experiment on March 04, 2009

			Speed (Factor B, j=1,2,3)		
			30km/hr (n= 1,..,5)	**50km/hr (n= 1,..,5)**	**70km/hr (n= 1,..,5)**
Ceramic Sensor	**Air Temperature (Factor A, j=1,2)**	**"-0.3 to 0.0"**	2721.6 3084.4 2404.0 2268.0 2721.6	2676.2 2540.1 2585.5 2812.3 2540.1	2630.8 2766.9 2721.6 2585.5 2222.6
		"-0.6 to -0.3"	2812.3 2268.0 2404.0 2358.7 2222.6	2449.4 2585.5 2721.6 3401.9 2766.9	2721.6 2585.5 2676.2 2676.2 2494.8

Table B. 21- ANOVA for air temperature and speed effects on the ceramic sensors, Mar. 04, 2009

Source of Variation	S of S	df	MS	f_0	P-Value	Significancy
Temperature, A	617.2	1	617.2	0.01	>0.25	
Speed, B	165145.5	2	82572.7	1.38	>0.25	
AB	192578.3	2	96289.1	1.61	0.1<P<0.25	Very Weak
Error	1433638.4	24	59734.9			
Total	1791979.4	29				

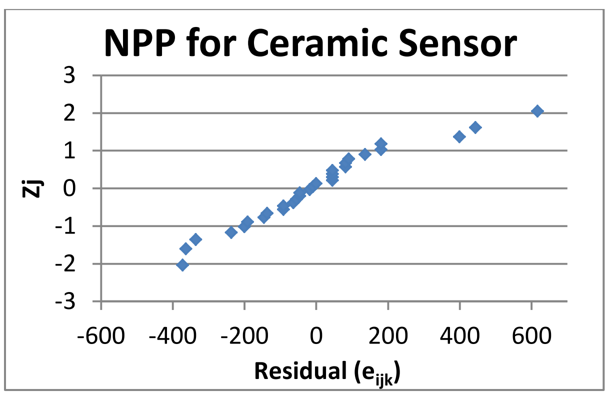


Figure B. 9- Plot of the ceramic sensor's residuals for the air temperature and speed factors

Appendix C

The Matching Algorithm between the WIM Station and the Main Scale House and Statistical Analysis for Heavy Truck at the Landfill Site

C.1 Procedure at the Main Scale House

The Main Scale House including computerized scale system with both inbound and outbound scales and its procedure definitions (Figure C. 1):

1. Region of Waterloo (R of W) and Dawson's trucks haul garbage to the landfill (Table C. 1)
2. In case of R of W and Dawson's trucks, when the time in and time out are the same it means that they have shipped garbage from Gate 2 to dump in Landfill and the system used the stored tares.
3. In other cases, when the time in and time out are the same it means that the trucks shipped outbound loads out of Waste Management at Gate I
4. Inbound loads (Table C. 2) are shipped to Waste Management (material types 1, 4, 17, 18 & 60 ship to landfill)
5. Outbound loads (Table C. 3) are taken out of Waste Management. The outbound trucks won't travel over the WIM sensors
6. "ST" in "Transaction No." coding means outbound load. The outbound trucks are mostly heavier than other trucks
7. In case of R of W and Dawson's trucks the computerized scale system uses stored tare

Table C. 1- Examples of license numbers for the R of W and Dawson trucks

R of W Trucks for Hauling Garbage		**Dawson Trucks for Hauling Garbage**	
No.	**License Number**	**No.**	**License Number**
1	3433VE	1	6080LN
2	3956NR	2	5101EM
3	5807WL	3	6335VF
4	7770TC	4	7905WJ
5	4519WX	5	9470RE
		6	WP1475
		7	6079LN

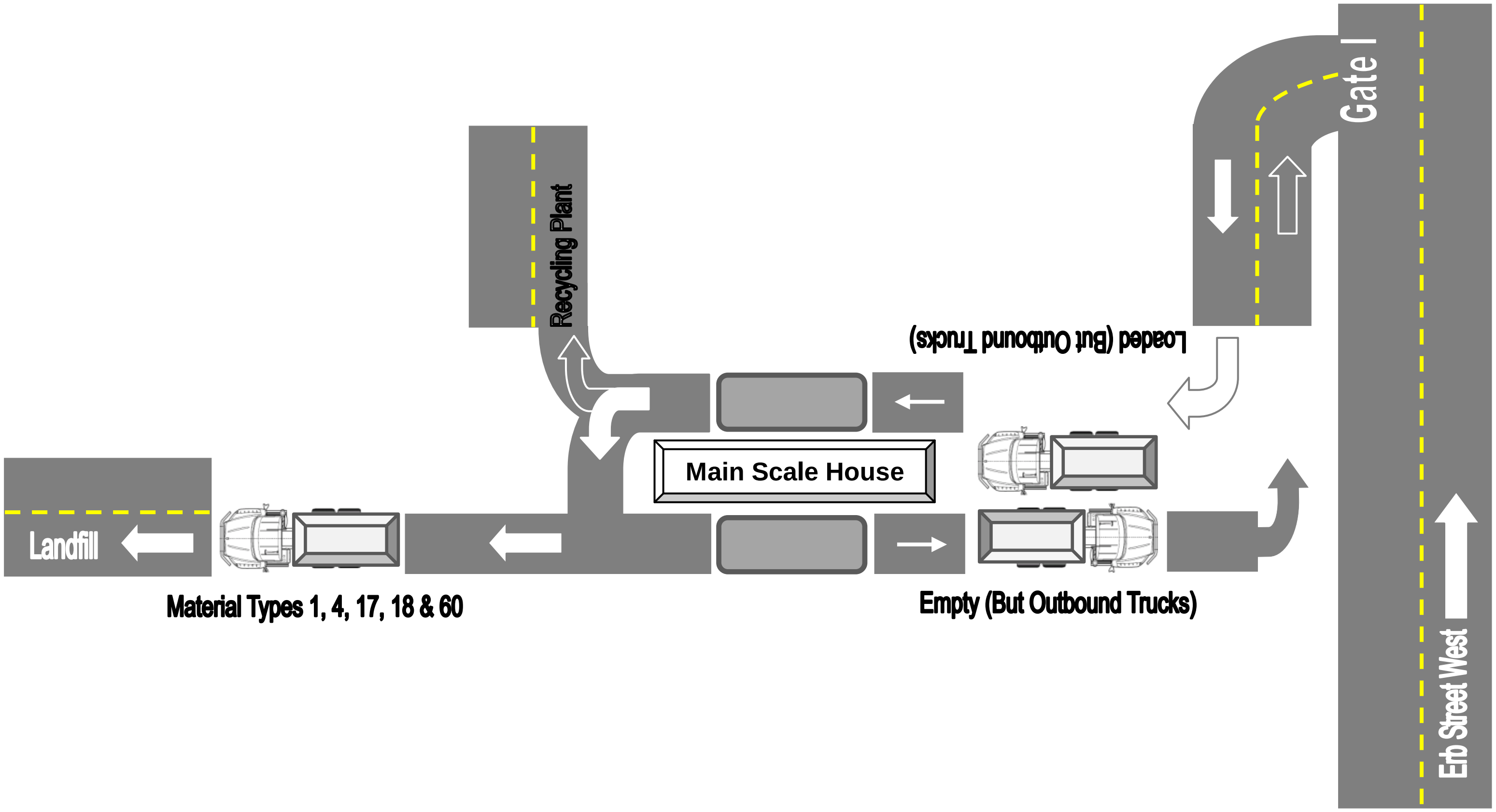


Figure C. 1- Main static scale procedure

Table C. 2- Inbound material types

	Material Type		Shipment	
No.	**Code**	**Description**	**Landfill**	**Other**
1	1	Municipal and Township Street Garbage	√	
2	2	Mixed Recycling (Municipal Blue Box Program)	?√	X
3	4	MRC Residue (Such as labels on cans etc.)		?X
4	6	Roadside Dumping		X
5	8	Yard Waste and Top Soil	√	X
6	13	Mixed Recycling		X
7	14	Concrete/Fill/Brick/Rubble	√	
8	17	Household Waste	√	
9	18	Mixed Industrial/Commercial/Institutional	√	
10	22	Scrap Metal White Goods		X
11	26	Surcharged Loads	?√	
12	31	Contaminated Soil	?√	
13	34	Tires (18" Rim or Smaller)		X
14	40	Leaves (Municipal &Township Only)		X
15	42	Water Efficiency		X
16	43	Pre-approved Building Material	?√	
17	44	CFC Removal Surcharge-First Unit		X
18	45	Litter-(Internal Use Only)	?√	
19	47	Shriners Club (Aluminum Cans)		X
20	50	Goodwill (Textile & Footwear)	?√	
21	53	Pallets-ICI		X
22	55	E-waste (Residential)-Per Unit up to Four (Each Unit)		X
23	58	E-waste (Commercial/Industrial/Institutional)		X
24	60	Cambridge Transfer-Landfill Material (Dawson)	√	
25	61	Cambridge Transfer-Woodchips (Dawson)		X
26	62	Cambridge Transfer-Recyclables (Dawson)		X
27	63	Cambridge Transfer-Yard Waste (Dawson)		X
28	64	Cambridge Transfer-Pallets (Dawson)		X
29	65	Adopt-A-Road Program		X
30	67	Organic Food Waste (Municipal Pilot)		X
31	69	Cambridge Transfer-Organic Residue (Dawson)	?√	
32	91	Customer Inquiry		X
33	99	Waived Tipping Fee Community Groups		X

Table C. 3- Outbound material types

	Material Type		Shipment	
No.	**Code**	**Description**	**Landfill**	**Other**
1	100	Corrugated Cardboard		√
2	101	Boxboard		√
3	102	Aluminum Cans		√
4	103	Steel Cans		√
5	104	Newsprint		√
6	105	Clear Glass		√
7	106	Colored Glass		√
8	107	Mixed Glass		√
9	108	Pet Bottles		√
10	109	Tires		√
11	110	HDPE Bottles		√
12	111	Scrap Metal / White Goods		√
13	112	Brush Wood Chips		√
14	113	Compost (Screened)		√
15	115	Pallet Wood Chips		√
16	120	Mixed Paper		√
17	121	Mixed Plastic		√
18	122	Plastic Film		√
19	123	Styrofoam		√
20	124	E-Waste		√
21	125	Polycoat Containers		√
22	150	Goodwill Textiles and Footwear		√
23	151	Pallets (Reusable)		√
24	152	Unfinished Compost		√
25	153	Ground Yard Waste		√
26	155	Compost (Unscreened)		√
27	156	Compost (Charitable/Community/Nonprofit)		√
28	157	Post Sort Mixed Fibre		√
29	158	Post Sort Mixed Containers		√
30	159	Unsorted Mixed Containers		√
31	160	Organic Food Waste		√
	200	Weight Tickets (Trucks and Cars for weights only)		

C.2 Matching Algorithm

The section below is the application developed by the Visual Basic 6 program for matching between the vehicles weighed at the static scale (at the Landfill site, upstream from the WIM station) and the vehicles passed over the WIM station.

‘Make an Excel file with the 1st to 5th sheets before running the program as follow:
‘1- WIM data of the month we are going to use
‘2- Static Data of the month we are going to use
‘3- Blank sheets 3 to 5
‘4- Save this file.
‘Click "AllinOne"
‘Step 3-Matching
‘1- Make the static time "Date+Time"
‘2- Make the WIM time "Date+Time"
‘3- Check the static and WIM times "Date+Time"
‘4- When WIM time is bigger than "Static time + Min normal travel time for a truck to reach the WIM site (30")"
‘5- The row of this match is recorded by "k=m"
‘6- This row is checked in the WIM data
‘7- If it shows that has Kistler data
‘8- Its WIM time is checked whether it is lower than "Static time + Max normal travel time for a truck to reach the WIM site (100")"
‘9- If it is so, the average GVW over P1 and P2 is divided by Static GVW
‘10- If this ratio is in the range -50% to + 50%
‘11- It is assumed that this is a matched item
‘12- Then that row is selected and some records from both static and WIM data is placed in the sheet
‘13- This is also done for IRD, MSI and ECM, which are one or two before (only if two trucks were traveling close together), one or two next and two to four next respectively.
‘14- The undesired records are deleted

VERSION 7.00

```
Object = "{F9043C88-F6F2-101A-A3C9-08002B2F49FB}#1.2#0"; "COMDLG32.OCX"
Object = "{831FDD16-0C5C-11D2-A9FC-0000F8754DA1}#2.0#0"; "MSCOMCTL.OCX"
Begin VB.Form Form1
   Caption         =   "WIManalyze"
   ClientHeight    =   3780
   ClientLeft      =   60
   ClientTop       =   450
   ClientWidth     =   12705
   LinkTopic       =   "Form1"
   ScaleHeight     =   3780
   ScaleWidth      =   12705
   StartUpPosition =   3                                        'Windows Default
   Begin VB.CommandButton SecondCompare
      Caption         =   "Second round Compare"
      Height          =   855
      Left            =   9840
      TabIndex        =   12
      Top             =   1200
      Width           =   2295
   End
   Begin VB.CommandButton WimSelect
      Caption         =   "WimSelect"
      Height          =   615
      Left            =   3600
      TabIndex        =   11
      Top             =   2160
      Width           =   3015
   End
   Begin VB.CommandButton Van_Select
      Caption         =   "Van Select"
      Height          =   615
      Left            =   3600
      TabIndex        =   10
      Top             =   1440
      Width           =   3015
   End
   Begin VB.CommandButton AllinOne
      BackColor       =   &H00FFFFFF&
      Caption         =   "All in One"
      Height          =   1095
      Left            =   8280
      MaskColor       =   &H00FFFFFF&
      TabIndex        =   9
      Top             =   600
      Width           =   1215
   End
```

```
Begin VB.CommandButton ConvertStatic
   Caption         =   "Convert Static 09"
   Height          =   615
   Left            =   120
   TabIndex        =   8
   Top             =   1440
   Width           =   3135
End
Begin VB.CommandButton Relationship
   Caption         =   "Relationship"
   Height          =   615
   Left            =   120
   TabIndex        =   7
   Top             =   2160
   Width           =   3135
End
Begin VB.CommandButton CalCheck
   Caption         =   "Check Van Calibration"
   Height          =   615
   Left            =   3600
   TabIndex        =   6
   Top             =   600
   Width           =   3015
End
Begin VB.TextBox DataNum
   Height          =   375
   Left            =   2160
   TabIndex        =   3
   Text            =   "0"
   Top             =   120
   Width           =   975
End
Begin VB.CommandButton DataBase
   Caption         =   "Create WIM DataBase"
   Height          =   735
   Left            =   120
   TabIndex        =   2
   Top             =   600
   Width           =   3135
End
Begin MSComctlLib.ProgressBar ProgressBar1
   Height          =   375
   Left            =   4440
   TabIndex        =   1
   Top             =   8880
   Width           =   2895
   _ExtentX        =   5106
   _ExtentY        =   661
   _Version        =   393216
   Appearance      =   1
End
Begin MSComDlg.CommonDialog dlg
   Left            =   120
   Top             =   0
   _ExtentX        =   847
   _ExtentY        =   847
   _Version        =   393216
   FileName        =   "aaa"
End
Begin VB.CommandButton Exit
   Caption         =   "Exit"
   Height          =   855
   Left            =   8280
   TabIndex        =   0
   Top             =   1920
   Width           =   1215
End
Begin MSComctlLib.StatusBar StatusBar
   Align           =   2  'Align Bottom
   Height          =   375
```

```
      Left            =   0
      TabIndex        =   5
      Top             =   3405
      Width           =   12705
      _ExtentX        =   22410
      _ExtentY        =   661
      _Version        =   393216
      BeginProperty Panels {8E3867A5-8586-11D1-B16A-00C0F0283628}
         NumPanels       =   4
         BeginProperty Panel1 {8E3867AB-8586-11D1-B16A-00C0F0283628}
            Object.Width           =   5080
            MinWidth        =   5080
         EndProperty
         BeginProperty Panel2 {8E3867AB-8586-11D1-B16A-00C0F0283628}
         EndProperty
         BeginProperty Panel3 {8E3867AB-8586-11D1-B16A-00C0F0283628}
            Object.Width           =   5080
            MinWidth        =   5080
         EndProperty
         BeginProperty Panel4 {8E3867AB-8586-11D1-B16A-00C0F0283628}
            Object.Width           =   5080
            MinWidth        =   5080
         EndProperty
      EndProperty
   End
   Begin VB.Label Label1
      Caption         =   "DataNumber:"
      Height          =   375
      Left            =   1080
      TabIndex        =   4
      Top             =   120
      Width           =   1215
   End
End
Attribute VB_Name = "Form1"
Attribute VB_GlobalNameSpace = False
Attribute VB_Creatable = False
Attribute VB_PredeclaredId = True
Attribute VB_Exposed = False
Dim xlBook As Excel.Workbook
Dim xlSheet As Excel.Worksheet

Private Sub AllinOne_Click()
Dim strFileName As String
Dim Source(120) As Integer
Dim IRDerror(3), Kiserror(3), MSIerror(3), ECMerror(3) As Integer
Dim IRDavr, KISavr, MSIavr, ECMavr As Single
On Error GoTo ErrHandler

Dim objApp As New Excel.Application
Dim exBook As Excel.Workbook
Dim exSheet, WimMonth, DBStatic, WimA, StaticA, DBRelation, DBRelation2 As Excel.Worksheet
strFileName = GetExcelFileName("Weigh in Motion", dlg)
Set exBook = objApp.Workbooks.Open(strFileName)

Set WimMonth = exBook.Worksheets(1)
Set DBStatic = exBook.Worksheets(2)
Set WimA = exBook.Worksheets(3)
Set StaticA = exBook.Worksheets(4)
Set DBRelation = exBook.Worksheets(5)
Set DBRelation2 = exBook.Worksheets(6)

'==========================================================
'Step 1: Select WIM data from original file, saved in datasheet 3
'==========================================================
Dim i, j, k, MVN As Integer
Dim ca(50) As Integer

k = 3
MVN = 0
```

```
StatusBar.Panels(1) = "1. Create WIM database..."
StatusBar.Panels(3) = Now
ProgressBar1.Min = 0
ProgressBar1.Max = 1
i = 6
Do Until WimMonth.Cells(i, 1) = ""
i = i + 100
Loop
DataNum.Text = i

i = 6
Do Until WimMonth.Cells(i, 1) = ""
   If (WimMonth.Cells(i, 26) > 0 And WimMonth.Cells(i, 26) < 9999) Then
      k = k + 1
      WimA.Cells(k, 1) = CStr(WimMonth.Cells(i, 2))                         'Day of the month
      WimA.Cells(k, 2) = CStr(WimMonth.Cells(i, 4)) + ":" + CStr(WimMonth.Cells(i, 5)) + ":" + CStr(WimMonth.Cells(i, 6)) 'time
'WimA.Cells is the new WIM sheet we are going to make

"       If WimMonth.Cells(i, 2) > 1 Then                          'Summer time adjustment by subtract 1 hour
"          j = WimMonth.Cells(i, 4) - 1
"       Else
"          j = WimMonth.Cells(i, 4)
"       End If
"       WimA.Cells(k, 2) = CStr(j) + ":" + CStr(WimMonth.Cells(i, 5)) + ":" + CStr(WimMonth.Cells(i, 6))

      WimA.Cells(k, 3) = WimMonth.Cells(i, 7)                   'Vehicle Number(VHNUM/S)[Station]
      WimA.Cells(k, 4) = WimMonth.Cells(i, 13)        'Lane Number(Ln)
      WimA.Cells(k, 5) = WimMonth.Cells(i, 14)        'Validation variable(Val)
      WimA.Cells(k, 6) = Format(WimMonth.Cells(i, 17), "00")          'Truck/Car variable(TC)
      WimA.Cells(k, 7) = WimMonth.Cells(i, 18)        'Vehicle classification(CA)
      WimA.Cells(k, 8) = WimMonth.Cells(i, 19)        'Sub-Category(ca)
      WimA.Cells(k, 9) = WimMonth.Cells(i, 20)        'Statistical Category(SC)
      WimA.Cells(k, 10) = Int(WimMonth.Cells(i, 23) * 1.609)          'Vehicle speed(SPEE) [mile to 1.609344 km/h]
      WimA.Cells(k, 11) = Format(WimMonth.Cells(i, 24) * 0.00305, "0.0")   'Vehicle length(LENG) [0.01 foot to 0.003048 meter]
      WimA.Cells(k, 12) = Format(WimMonth.Cells(i, 26) * 0.00305, "0.0")   'Wheel base[first-last axle](TODT)
      WimA.Cells(k, 13) = Int(WimMonth.Cells(i, 27) * 45.36)          'GVW on P1 (TWT1) [100 pound to 45.3592 kg]
      WimA.Cells(k, 14) = Int(WimMonth.Cells(i, 28) * 45.36)          'GVW on P2 (TWT2)
      WimA.Cells(k, 15) = Int(WimMonth.Cells(i, 29) * 45.36)          'GVW on P1/P2 (TWT3)
      If WimA.Cells(k, 4) = 1 Then                                            'Kistler (Shahram)
         MVN = MVN + 1                                                'Monthly vehicle number based on Kistler sensor
         ca(WimA.Cells(k, 8)) = ca(WimA.Cells(k, 8)) + 1              'Monthly vehicle number on each sub-categories
         ProgressBar1.Value = i / DataNum.Text
         StatusBar.Panels(2) = i
      End If

   End If
   i = i + 1
   StatusBar.Panels(4) = Now
Loop

k = k + 2
WimA.Cells(k, 3) = "Monthly Vehicle Number:"
WimA.Cells(k, 6) = MVN
WimA.Cells(k + 1, 1) = "ca number:"
k = k + 2
For i = 0 To 49
   WimA.Cells(k, i + 3) = i
   WimA.Cells(k + 1, i + 3) = ca(i)
Next
ProgressBar1.Value = 0
'=========================================================
'Step 2: Choose and Convert Static data, saved in datasheet 4
'=========================================================
k = 3
StatusBar.Panels(1) = "2. Static data select"
i = 10
Do Until DBStatic.Cells(i, 3) = ""
i = i + 100
Loop
DataNum.Text = i
```

```
ProgressBar1.Min = 0
ProgressBar1.Max = i
ProgressBar1.Value = 0
i = 10   'Static database start from line 10
j = 3
Dim Matype As String
Do Until DBStatic.Cells(i, 3) = ""                                   'Till end of file
   On Error Resume Next
   Matype = DBStatic.Cells(i, 20)
   If Matype <> "" And DBStatic.Cells(i, 7) <> "T" And DBStatic.Cells(i, 22) <> 0 Then
      'If ((Matype = 1) Or (Matype = 17) Or (Matype = 18) Or (Matype = 60)) Then
      If ((Matype = 1) Or (Matype = 8) Or (Matype = 14) Or (Matype = 17) Or (Matype = 18) Or (Matype = 60)) Then
         StaticA.Cells(j, 1) = Day(DBStatic.Cells(i, 3))     'Day of the year
         StaticA.Cells(j, 2) = j - 2
         StaticA.Cells(j, 3) = DBStatic.Cells(i, 5)           'Transaction #
         StaticA.Cells(j, 4) = DBStatic.Cells(i, 14)          'Licence #
         StaticA.Cells(j, 5) = DBStatic.Cells(i, 15)          'Time In
         StaticA.Cells(j, 6) = DBStatic.Cells(i, 16)          'Time Out
         StaticA.Cells(j, 7) = DBStatic.Cells(i, 20)          'Material Type
         StaticA.Cells(j, 8) = DBStatic.Cells(i, 22)          'GVW
         StaticA.Cells(j, 9) = DBStatic.Cells(i, 24)          'Tare Weight
         If DBStatic.Cells(i, 5) <> DBStatic.Cells(i + 1, 5) Then                'Exclude repeated transactions
            j = j + 1
         End If
      End If
   End If
ProgressBar1.Value = i
StatusBar.Panels(2) = i
i = i + 1
StatusBar.Panels(4) = Now
Loop

StatusBar.Panels(2) = 0
ProgressBar1.Value = 0
'=========================================================
'Step 3: WIM - Static data Relationship, saved in datasheet 5
'=========================================================
Dim WeightTime, WimTime, Ratio As Single
k = 3
StatusBar.Panels(1) = "3. WIM-Static compare."
i = 3
Do Until StaticA.Cells(i, 2) = ""
i = i + 100                              ' "+100" is just for speeding up in reading of the worksheet
Loop

DataNum.Text = i
ProgressBar1.Min = 0
ProgressBar1.Max = i
i = 3
j = 4
k = 4
m = 4
'WIM Seleted "WimA"
'(k, 1)     (k, 2)  (k, 3)  (k, 4)   (k, 5)     (k, 6)  (k, 7)  (k, 8)  (k, 9)
'Day(month) time     Veh.#   Lane#    Validation TC      CA      ca      Stat_Cat(SC)
'(k, 10)    (k, 11) (k, 12)     (k, 13)         (k, 14)         (k, 15)
' SPEE      LENG    Wheel base  GVW on P1(TWT1) GVW on P2(TWT2) GVW on P1/P2 (TWT3)

'May need to add axle weights, if the axle weights can be approximated
'May need to add axle spacing for classes 6, 7 and 10
'Static selected "StaticA"
'(j, 1) (j, 2)  (j, 3)      (j, 4)      (j, 5)  (j, 6)      (j, 7)      (j, 8)  (j, 9)
'DD(yy) No.     Trans. #    Licence #   Time In Time Out    Mat.Typ.    GVW     Tare Weight

Do Until StaticA.Cells(i, 1) = ""                            'Compare static data and WIM data
   WeightTime = StaticA.Cells(i, 1) + CSng(CDate(StaticA.Cells(i, 5)))

'date+time (Pick the first "Time in" in static data for looking for it in the WIM data)

' 1-WimTime should first be compensated to match the internet time (Edward considered 136 sec)
```

```
' 2-then the WimTime should be 50 to 80 sec higher than the static time for a specific truck.
' 3-Considering in the 1st "10 sec" trucks travel 55 m (ave. 20 km/hr, (real: 0-40 km/hr)),
' 4-and in the 2nd "10 sec" trucks travel 125 m (ave. 45 km/hr, (real: 40-50 km/hr))
' 5-We have 825 m - (55 m + 125 m)= 645 m
' 6-Then for ave. 70 km/hr (real: 50-90 km/hr)it takes 33 sec
' 7-and for ave. 50 km/hr (real: 40-60 km/hr)it takes 46 sec
' 8-and for ave. 40 km/hr (real: 30-50 km/hr)it takes 58 sec
' 9-Then min and max times are 20 + 33 = 53 sec and 20 + 58 = 78 sec
' 10-Therefore, 825 m from SWS to WIM takes approx. 50 to 80 seconds
' 11-The following loop searches the "WimTime" in the first 216 second of static data(Shahram)
   WimTime = WimA.Cells(m, 1) + WimA.Cells(m, 2)
   Do Until (WimTime > WeightTime - 0.0025)                    'Delay 216" (Min time difference)
      m = m + 1
      WimTime = WimA.Cells(m, 1) + WimA.Cells(m, 2)
   Loop
   k = m                                                       'The matched times

RepeatWIM:
   Do Until (WimA.Cells(k, 4) = 1)                             'Lane 1: Kistler sensors
      k = k + 1
      If WimA.Cells(k, 1) = "" Then GoTo CompareOver
      WimTime = WimA.Cells(k, 1) + WimA.Cells(k, 2)            ' Kistler WimTime
   Loop

   If (WimTime < WeightTime + 0.0025) Then             '216" (Max time difference)
      Ratio = WimA.Cells(k, 15) / StaticA.Cells(i, 8)      '(GVW on P1/P2)/(Static GVW)
      If (Ratio > 0.5) And (Ratio < 1.5) Then             '50% error limitation
         DBRelation.Cells(j, 1) = WimA.Cells(k, 1)         'Day of month (Kistler)
         DBRelation.Cells(j, 2) = Format(WimA.Cells(k, 2), "hh:mm:ss")                    'Time (Kistler)

         DBRelation.Cells(j, 35) = WimTime

         DBRelation.Cells(j, 3) = WimA.Cells(k, 3)         'VHNUM (Kistler)
         DBRelation.Cells(j, 4) = WimA.Cells(k, 8)         'ca (Kistler)
         DBRelation.Cells(j, 5) = WimA.Cells(k, 10)        'Speed (Kistler)
         DBRelation.Cells(j, 6) = WimA.Cells(k, 12)        'TODT (Kistler)
         If WimA.Cells(k - 1, 4) = 0 Then                  'IRD
            DBRelation.Cells(j, 7) = WimA.Cells(k - 1, 15)
         ElseIf WimA.Cells(k - 2, 4) = 0 Then              'Two vehicles may visit these sensors very close to each other
            DBRelation.Cells(j, 7) = WimA.Cells(k - 2, 15)
         End If
         DBRelation.Cells(j, 8) = WimA.Cells(k, 15)        'Kistler
         If WimA.Cells(k + 1, 4) = 2 Then                  'MSI
            DBRelation.Cells(j, 9) = WimA.Cells(k + 1, 15)
         ElseIf WimA.Cells(k + 2, 4) = 2 Then
            DBRelation.Cells(j, 9) = WimA.Cells(k + 2, 15)
         End If

         If WimA.Cells(k + 2, 4) = 3 Then                  'ECM
            DBRelation.Cells(j, 10) = WimA.Cells(k + 2, 15)
         ElseIf WimA.Cells(k + 3, 4) = 3 Then
            DBRelation.Cells(j, 10) = WimA.Cells(k + 3, 15)
         ElseIf WimA.Cells(k + 4, 4) = 3 Then
            DBRelation.Cells(j, 10) = WimA.Cells(k + 4, 15)
         End If

         DBRelation.Cells(j, 11) = Format(StaticA.Cells(i, 5), "hh:mm")      'Static time in
         DBRelation.Cells(j, 12) = StaticA.Cells(i, 6)                   'Static time out
         DBRelation.Cells(j, 13) = StaticA.Cells(i, 8)                   'GVW
         DBRelation.Cells(j, 14) = StaticA.Cells(i, 9)                   'Tare weight
         DBRelation.Cells(j, 15) = StaticA.Cells(i, 3)                   'Transaction number
         DBRelation.Cells(j, 16) = StaticA.Cells(i, 4)                   'Plate number
         DBRelation.Cells(j, 17) = StaticA.Cells(i, 7)                   'Material Type
         DBRelation.Cells(j, 18) = Format(Ratio - 1, "0.000")           'Error in estimation
         DBRelation.Cells(j, 19) = Format((DBRelation.Cells(j, 2) - CSng(DBRelation.Cells(j, 11))) * 24 * 3600, "##0")
                                    ' Kistler Time minus Static time
         DBRelation.Cells(j, 20) = Format(DBRelation.Cells(j, 7) / DBRelation.Cells(j, 13) - 1, "0.000")             'IRD error
         DBRelation.Cells(j, 21) = Format(DBRelation.Cells(j, 9) / DBRelation.Cells(j, 13) - 1, "0.000")             'MSI error
         DBRelation.Cells(j, 22) = Format(DBRelation.Cells(j, 10) / DBRelation.Cells(j, 13) - 1, "0.000")            'ECM error
```

```
        If DBRelation.Cells(j, 3) = DBRelation.Cells(j - 1, 3) Then                 'Delete repeated records
          If Abs(DBRelation.Cells(j, 18)) > Abs(DBRelation.Cells(j - 1, 18)) Then
            DBRelation.Rows(j).Delete                                               'Delete the bigger errors
          Else
            DBRelation.Rows(j - 1).Delete
          End If
          j = j - 1
        ElseIf ((DBRelation.Cells(j, 1) + DBRelation.Cells(j, 2)) < (DBRelation.Cells(j - 1, 1) + DBRelation.Cells(j - 1, 2))) And j > 4
Then                                            'The time of this record is lesser than preceding record
          DBRelation.Rows(j).Delete
          j = j - 1
        End If

        If DBRelation.Cells(j, 15) = DBRelation.Cells(j - 1, 15) Then               'Changed from 14 to 15 to define static transaction
number @ May 27, 2009
          If Abs(DBRelation.Cells(j, 18)) > Abs(DBRelation.Cells(j - 1, 18)) Then
            DBRelation.Rows(j).Delete
          Else
            DBRelation.Rows(j - 1).Delete
          End If
          j = j - 1
        End If

        j = j + 1
      End If
  End If
  k = k + 1
  WimTime = WimA.Cells(k, 1) + WimA.Cells(k, 2)
  If (WimTime < WeightTime + 0.0025) Then GoTo RepeatWIM

ProgressBar1.Value = i
StatusBar.Panels(2) = i
StatusBar.Panels(4) = Now
i = i + 1
Loop
```

CompareOver:

```
For i = 0 To 2
  IRDerror(i) = 0
  Kiserror(i) = 0
  MSIerror(i) = 0
  ECMerror(i) = 0
Next

DataNum.Text = j
ProgressBar1.Min = 0
ProgressBar1.Max = j

i = 4
StatusBar.Panels(1) = "4. Start WIM-Static analysis."
Do Until DBRelation.Cells(i, 17) = ""
  Source(DBRelation.Cells(i, 17)) = Source(DBRelation.Cells(i, 17)) + 1
  If Abs(DBRelation.Cells(i, 18)) < 0.05 Then
    Kiserror(0) = Kiserror(0) + 1
  ElseIf Abs(DBRelation.Cells(i, 18)) < 0.1 Then
    Kiserror(1) = Kiserror(1) + 1
  ElseIf Abs(DBRelation.Cells(i, 18)) < 0.2 Then
    Kiserror(2) = Kiserror(2) + 1
  End If

  If Abs(DBRelation.Cells(i, 20)) < 0.05 Then
    IRDerror(0) = IRDerror(0) + 1
  ElseIf Abs(DBRelation.Cells(i, 20)) < 0.1 Then
    IRDerror(1) = IRDerror(1) + 1
  ElseIf Abs(DBRelation.Cells(i, 20)) < 0.2 Then
    IRDerror(2) = IRDerror(2) + 1
  End If
  If Abs(DBRelation.Cells(i, 21)) < 0.05 Then
    MSIerror(0) = MSIerror(0) + 1
  ElseIf Abs(DBRelation.Cells(i, 21)) < 0.1 Then
```

```
      MSIerror(1) = MSIerror(1) + 1
   ElseIf Abs(DBRelation.Cells(i, 21)) < 0.2 Then
      MSIerror(2) = MSIerror(2) + 1
   End If
   If Abs(DBRelation.Cells(i, 22)) < 0.05 Then
      ECMerror(0) = ECMerror(0) + 1
   ElseIf Abs(DBRelation.Cells(i, 22)) < 0.1 Then
      ECMerror(1) = ECMerror(1) + 1
   ElseIf Abs(DBRelation.Cells(i, 22)) < 0.2 Then
      ECMerror(2) = ECMerror(2) + 1
   End If

   i = i + 1
   ProgressBar1.Value = i
   StatusBar.Panels(2) = i
Loop

k = 4
For i = 0 To 119
   If Source(i) <> 0 Then
      DBRelation.Cells(k, 23) = i
      DBRelation.Cells(k, 24) = Source(i)
      k = k + 1
   End If
Next

   DBRelation2.Cells(3, 25) = "Error"
   DBRelation2.Cells(4, 25) = "<5%"
   DBRelation2.Cells(5, 25) = "5-10%"
   DBRelation2.Cells(6, 25) = "10-20%"
   DBRelation2.Cells(7, 25) = "<20%"
   DBRelation2.Cells(8, 23) = "Match"

   DBRelation2.Cells(3, 26) = "IRDn"
   DBRelation2.Cells(3, 27) = "Kistn"
   DBRelation2.Cells(3, 28) = "MSIn"
   DBRelation2.Cells(3, 29) = "ECMn"
   DBRelation2.Cells(3, 30) = "IRD%"
   DBRelation2.Cells(3, 31) = "Kist%"
   DBRelation2.Cells(3, 32) = "MSI%"
   DBRelation2.Cells(3, 33) = "ECM%"

For i = 0 To 2
   DBRelation.Cells(4 + i, 25) = Format(IRDerror(i), "0.000")
   DBRelation.Cells(4 + i, 26) = Format(Kiserror(i), "0.000")
   DBRelation.Cells(4 + i, 27) = Format(MSIerror(i), "0.000")
   DBRelation.Cells(4 + i, 28) = Format(ECMerror(i), "0.000")
   DBRelation.Cells(4 + i, 30) = Format(IRDerror(i) / ProgressBar1.Value, "0.000")
   DBRelation.Cells(4 + i, 31) = Format(Kiserror(i) / ProgressBar1.Value, "0.000")
   DBRelation.Cells(4 + i, 32) = Format(MSIerror(i) / ProgressBar1.Value, "0.000")
   DBRelation.Cells(4 + i, 33) = Format(ECMerror(i) / ProgressBar1.Value, "0.000")
Next
DBRelation.Cells(7, 25) = ProgressBar1.Value 'total matched records of the database
DBRelation.Cells(7, 26) = ProgressBar1.Value
DBRelation.Cells(7, 27) = ProgressBar1.Value
DBRelation.Cells(7, 28) = ProgressBar1.Value
StatusBar.Panels(2) = 0
'========================================================
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
StatusBar.Panels(4) = Now
StatusBar.Panels(1) = "WIM-Static completed."
Exit Sub

ErrHandler:
MsgBox "VB Error Number" & Err.Number
StatusBar.Panels(1) = "Error Happened."
```

```
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
End Sub     'End of "AllinOne" button

Private Sub CalCheck_Click()
'sub class=9
'valid=0
'minimum weight>30
'FAW:27-41
'GVW:43-79

On Error GoTo ErrHandler
Dim objApp As New Excel.Application
Dim exSheet, WimMonth, DBMonth As Excel.Worksheet
Dim exBook As Excel.Workbook
Dim strFileName As String
strFileName = GetExcelFileName("Weigh in Motion", dlg)
Set exBook = objApp.Workbooks.Open(strFileName)
Set WimMonth = exBook.Worksheets(1)
Set DBMonth = exBook.Worksheets(2)

Dim i, j, k, MVN As Integer
Dim Small, Midium, Big As Integer
Dim ca(50) As Integer
Dim WeightTime As Date
Dim WimTime As Single
Dim Wim2 As Boolean

MVN = 0
StatusBar.Panels(1) = "Checking if meet auto- calibration ..."
ProgressBar1.Min = 0
ProgressBar1.Max = 1
DBMonth.Cells(1, 1) = "Date"
DBMonth.Cells(1, 2) = "Time"
DBMonth.Cells(1, 3) = "LN"
DBMonth.Cells(1, 4) = "Valid"
DBMonth.Cells(1, 5) = "TC"
DBMonth.Cells(1, 6) = "ca"
DBMonth.Cells(1, 7) = "Speed"
DBMonth.Cells(1, 8) = "TODT"
DBMonth.Cells(1, 9) = "TWT1"
DBMonth.Cells(1, 10) = "TWT2"
DBMonth.Cells(1, 11) = "TWT3"
FlexGrid.TextMatrix(0, 9) = "TWT3"
k = 1
For i = 7 To DataNum.Text
   If (WimMonth.Cells(i, 19) = 9 And WimMonth.Cells(i, 28) < 80 And WimMonth.Cells(i, 28) > 42) Then
      k = k + 1
      DBMonth.Cells(k, 1) = CStr(WimMonth.Cells(i, 2))              'Date
      DBMonth.Cells(k, 2) = CStr(WimMonth.Cells(i, 4)) + ":" + CStr(WimMonth.Cells(i, 5)) + ":" + CStr(WimMonth.Cells(i, 6))
'time
      DBMonth.Cells(k, 3) = WimMonth.Cells(i, 13)                    'Lane Number(Ln)
      DBMonth.Cells(k, 4) = WimMonth.Cells(i, 14)                    'Validation variable(Val)
      DBMonth.Cells(k, 5) = WimMonth.Cells(i, 17)                    'Truck/Car Variable(TC)
      DBMonth.Cells(k, 6) = WimMonth.Cells(i, 19)                    'Sub-Category(ca)
      DBMonth.Cells(k, 7) = WimMonth.Cells(i, 22)                   'Vehicle speed(SPEE)
      DBMonth.Cells(k, 8) = WimMonth.Cells(i, 25)                   'Wheel base[first-last axle](TODT)
      DBMonth.Cells(k, 9) = WimMonth.Cells(i, 26)                    'GVW on P1 (TWT1)
      DBMonth.Cells(k, 10) = WimMonth.Cells(i, 27)                   'GVW on P2 (TWT2)
      DBMonth.Cells(k, 11) = WimMonth.Cells(i, 28)                   'GVW on P1/P2 (TWT3)
      ProgressBar1.Value = i / DataNum.Text
      StatusBar.Panels(2) = i
   End If
Next

StatusBar.Panels(1) = "Check Calibration completed."
ProgressBar1.Value = 0
```

```
ErrHandler:
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing

End Sub
Private Sub ConvertStatic_Click()

On Error GoTo ErrHandler

Dim i, j, k, Wnum, Snum As Integer
Dim WeightTime, WimTime, Ratio As Single
Dim Wim2 As Boolean
Dim SDate As String
Dim objApp As New Excel.Application
Dim exSheet, Static10, Static11, DBStatic10 As Excel.Worksheet
Dim exBook As Excel.Workbook
Dim strFileName As String

strFileName = GetExcelFileName("Weigh in Motion", dlg)
Set exBook = objApp.Workbooks.Open(strFileName)
Set Static10 = exBook.Worksheets(3)
Set DBStatic10 = exBook.Worksheets(4)

k = 3
MVN = 0
StatusBar.Panels(1) = "Start WIM-Static select"
StatusBar.Panels(3) = Now
i = 8
Do Until Static10.Cells(i, 3) = ""
i = i + 100
Loop
DataNum.Text = i

ProgressBar1.Min = 0
ProgressBar1.Max = i
ProgressBar1.Value = 0

j = 1
        DBStatic10.Cells(j, 1) = "Date"
        DBStatic10.Cells(j, 2) = "Number"
        DBStatic10.Cells(j, 3) = "TranNum"
        DBStatic10.Cells(j, 4) = "Plate"
        DBStatic10.Cells(j, 5) = "TimeIn"
        DBStatic10.Cells(j, 6) = "TimeOut"
        DBStatic10.Cells(j, 7) = "MaterialType"
        DBStatic10.Cells(j, 8) = "GrossWeight"
        DBStatic10.Cells(j, 9) = "TareWeight"
i = 8
j = 2
k = 4
Do Until Static10.Cells(i, 3) = ""
   If Static10.Cells(i, 2) <> "" Then
      SDate = Static10.Cells(i, 2)
   End If

   If Static10.Cells(i, 15) > 3 And (Static10.Cells(i, 11) <> Static10.Cells(i, 12)) Then 'Material type<>1,2," "

        DBStatic10.Cells(j, 1) = SDate  'date
        DBStatic10.Cells(j, 2) = j - 1
        DBStatic10.Cells(j, 3) = Static10.Cells(i, 4)
        DBStatic10.Cells(j, 4) = Static10.Cells(i, 10)
        DBStatic10.Cells(j, 5) = Static10.Cells(i, 11)
        DBStatic10.Cells(j, 6) = Static10.Cells(i, 12)
        DBStatic10.Cells(j, 7) = Static10.Cells(i, 15)
        DBStatic10.Cells(j, 8) = Static10.Cells(i, 17)
        DBStatic10.Cells(j, 9) = Static10.Cells(i, 19)
```

```
            If Static10.Cells(i, 4) <> Static10.Cells(i - 1, 4) Then
               j = j + 1
            End If
   End If

ProgressBar1.Value = i
StatusBar.Panels(2) = i
i = i + 1
Loop
StatusBar.Panels(2) = 0
StatusBar.Panels(4) = Now
StatusBar.Panels(1) = "WIM-Static select completed."
ProgressBar1.Value = 0

ErrHandler:
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
End Sub

Private Sub DataBase_Click()
Dim i, j, k, MVN As Integer
Dim Small, Midium, Big As Integer
Dim ca(50) As Integer
Dim WeightTime As Date
Dim WimTime As Single
Dim Wim2 As Boolean
Dim objApp As New Excel.Application
Dim exSheet, WimMonth, DBMonth As Excel.Worksheet
Dim exBook As Excel.Workbook
Dim strFileName As String

On Error GoTo ErrHandler

strFileName = GetExcelFileName("Weigh in Motion", dlg)
Set exBook = objApp.Workbooks.Open(strFileName)
Set exSheet = exBook.Worksheets(1)
Set WimMonth = exBook.Worksheets(1)
Set DBMonth = exBook.Worksheets(2)

k = 3
MVN = 0
StatusBar.Panels(1) = "Start create database..."
StatusBar.Panels(3) = Now
ProgressBar1.Min = 0
ProgressBar1.Max = 1
i = 6
Do Until WimMonth.Cells(i, 1) = ""
i = i + 100
Loop
DataNum.Text = i

i = 6
Do Until WimMonth.Cells(i, 1) = ""
   If (WimMonth.Cells(i, 26) > 0 And WimMonth.Cells(i, 26) < 9999) Then
      k = k + 1
      DBMonth.Cells(k, 1) = CStr(WimMonth.Cells(i, 2)) 'date
      DBMonth.Cells(k, 2) = CStr(WimMonth.Cells(i, 4)) + ":" + CStr(WimMonth.Cells(i, 5)) + ":" + CStr(WimMonth.Cells(i, 6))
'time
      DBMonth.Cells(k, 3) = WimMonth.Cells(i, 7)       'Vehicle Number(VHNUM/S)[Station]
      DBMonth.Cells(k, 4) = WimMonth.Cells(i, 13)      'Lane Number(Ln)
      DBMonth.Cells(k, 5) = WimMonth.Cells(i, 14)      'Validation variable(Val)
      DBMonth.Cells(k, 6) = WimMonth.Cells(i, 17)      'Truck/Car Variable(TC)
      DBMonth.Cells(k, 7) = WimMonth.Cells(i, 18)      'Vehicle classification(CA)
      DBMonth.Cells(k, 8) = WimMonth.Cells(i, 19)      'Sub-Category(ca)
      DBMonth.Cells(k, 9) = WimMonth.Cells(i, 20)      'Statistical Category(SC)
      DBMonth.Cells(k, 10) = Int(WimMonth.Cells(i, 23) * 1.609)  'Vehicle speed (SPEE) [mile to 1.609344 km/h]
```

```
    DBMonth.Cells(k, 11) = Format(WimMonth.Cells(i, 24) * 0.00305, "0.0")          'Vehicle length (LENG) [0.01 foot to
0.003048 meter]
    DBMonth.Cells(k, 12) = Format(WimMonth.Cells(i, 26) * 0.00305, "0.0")          'Wheel base [first-last axle](TODT)
    DBMonth.Cells(k, 13) = Int(WimMonth.Cells(i, 27) * 45.36)  'GVW on P1 (TWT1) [100 pound to 45.3592 kg]
    DBMonth.Cells(k, 14) = Int(WimMonth.Cells(i, 28) * 45.36)  ' GVW on P2 (TWT2)
    DBMonth.Cells(k, 15) = Int(WimMonth.Cells(i, 29) * 45.36)  ' GVW, P1/P2 (TWT3)
    If DBMonth.Cells(k, 4) = 1 Then
      MVN = MVN + 1                    'Monthly vehicle number (Kistler sensor)
      ca(DBMonth.Cells(k, 8)) = ca(DBMonth.Cells(k, 8)) + 1            'Monthly vehicle number on each sub-categories
      ProgressBar1.Value = i / DataNum.Text
      StatusBar.Panels(2) = i
    End If
  End If
   i = i + 1
Loop

k = k + 2
DBMonth.Cells(k, 3) = "Monthly Vehicle Number:"
DBMonth.Cells(k, 6) = MVN
DBMonth.Cells(k + 1, 1) = "ca number:"
k = k + 2
For i = 0 To 49
   DBMonth.Cells(k, i + 3) = i
   DBMonth.Cells(k + 1, i + 3) = ca(i)
Next
StatusBar.Panels(4) = Now
StatusBar.Panels(1) = "Create database completed."

ProgressBar1.Value = 0

ErrHandler:
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
End Sub

Private Sub Exit_Click()
Unload Me
Close
End Sub

Private Sub Relationship_Click()
On Error GoTo ErrHandler
Dim objApp As New Excel.Application
Dim exSheet, WimMonth, DBMonth, DBStatic, DBRelation As Excel.Worksheet
Dim exBook As Excel.Workbook
Dim strFileName As String
strFileName = GetExcelFileName("Weigh in Motion", dlg)
Set exBook = objApp.Workbooks.Open(strFileName)
Set WimMonth = exBook.Worksheets(1)
Set DBMonth = exBook.Worksheets(2)
Set DBStatic = exBook.Worksheets(3)
Set DBRelation = exBook.Worksheets(4)

Dim i, j, k, m, Wnum, Snum As Integer
Dim WeightTime, WimTime, Ratio As Single
Dim Wim2 As Boolean

k = 3
MVN = 0
StatusBar.Panels(1) = "Start WIM-Static..."
StatusBar.Panels(3) = Now
i = 2
Do Until DBStatic.Cells(i, 2) = ""
i = i + 100
Loop
DataNum.Text = i
```

```
ProgressBar1.Min = 0
ProgressBar1.Max = i

i = 2
j = 4
k = 4
m = 4
Do Until DBStatic.Cells(i, 1) = ""  'compare static data and WIM data
   WeightTime = Day(DBStatic.Cells(i, 1)) + CSng(CDate(DBStatic.Cells(i, 5)))    'Date + Time

   WimTime = DBMonth.Cells(m, 1) + DBMonth.Cells(m, 2)                        '1s=0.000011574  3.6s=0.00004167
   Do Until (WimTime > WeightTime - 0.0007)
      m = m + 1
      WimTime = DBMonth.Cells(m, 1) + DBMonth.Cells(m, 2)  'DBMonth.Cells(m, 1) * 1.00004167= 3.6s/day
   Loop

   k = m
RepeatWIM:
   Do Until (WimTime > WeightTime - 0.0007) And (DBMonth.Cells(k, 4) = 1) And DBMonth.Cells(k, 1) <> ""
      k = k + 1
      WimTime = DBMonth.Cells(k, 1) + DBMonth.Cells(k, 2)
   Loop

   If (WimTime < WeightTime + 0.0025) And DBMonth.Cells(k, 1) <> "" Then   '216 seconds
      Ratio = DBMonth.Cells(k, 15) / DBStatic.Cells(i, 8)
      If (Ratio > 0.5) And (Ratio < 1.5) Then '50% error limitatioin
         DBRelation.Cells(j, 1) = DBMonth.Cells(k, 1) 'date
         DBRelation.Cells(j, 2) = Format(DBMonth.Cells(k, 2), "hh:mm:ss") 'time
         DBRelation.Cells(j, 3) = DBMonth.Cells(k, 3) 'VHNUM
         DBRelation.Cells(j, 4) = DBMonth.Cells(k, 8) 'ca
         DBRelation.Cells(j, 5) = DBMonth.Cells(k, 10) ' Speed
         DBRelation.Cells(j, 6) = DBMonth.Cells(k, 12) ' TODT
         If DBMonth.Cells(k - 1, 4) = 0 Then     'IRD
            DBRelation.Cells(j, 7) = DBMonth.Cells(k - 1, 15)
         End If
         DBRelation.Cells(j, 8) = DBMonth.Cells(k, 15) 'Kistler
         If DBMonth.Cells(k + 1, 4) = 2 Then 'MSI
            DBRelation.Cells(j, 9) = DBMonth.Cells(k + 1, 15)
         End If
         If DBMonth.Cells(k + 2, 4) = 3 Then 'ECM
            DBRelation.Cells(j, 10) = DBMonth.Cells(k + 2, 15)
         End If
         DBRelation.Cells(j, 11) = Format(DBStatic.Cells(i, 5), "hh:mm") 'Static time
         DBRelation.Cells(j, 12) = DBStatic.Cells(i, 4) 'Plate number
         DBRelation.Cells(j, 13) = DBStatic.Cells(i, 8) 'GVW
         DBRelation.Cells(j, 14) = DBStatic.Cells(i, 3) ' Transaction number
         DBRelation.Cells(j, 15) = Ratio - 1
         DBRelation.Cells(j, 16) = DBRelation.Cells(j, 2) + DBRelation.Cells(j, 1) - DBRelation.Cells(j, 11)

         If DBRelation.Cells(j, 3) = DBRelation.Cells(j - 1, 3) Then
            If Abs(DBRelation.Cells(j, 15)) > Abs(DBRelation.Cells(j - 1, 15)) Then
               DBRelation.Rows(j).Delete
            Else
               DBRelation.Rows(j - 1).Delete
            End If
            j = j - 1
         ElseIf (DBRelation.Cells(j, 1) + DBRelation.Cells(j, 2)) < (DBRelation.Cells(j - 1, 1) + DBRelation.Cells(j - 1, 2)) Then
            DBRelation.Rows(j).Delete
            j = j - 1
         End If

         If DBRelation.Cells(j, 14) = DBRelation.Cells(j - 1, 14) Then
            If Abs(DBRelation.Cells(j, 15)) > Abs(DBRelation.Cells(j - 1, 15)) Then
               DBRelation.Rows(j).Delete
            Else
               DBRelation.Rows(j - 1).Delete
            End If
            j = j - 1
         End If
        j = j + 1
```

```
      End If
    End If
    k = k + 1
    WimTime = DBMonth.Cells(k, 1) + DBMonth.Cells(k, 2)
    If (WimTime < WeightTime + 0.0025) Then GoTo RepeatWIM

ProgressBar1.Value = i
StatusBar.Panels(2) = i
i = i + 1
Loop
StatusBar.Panels(2) = 0

StatusBar.Panels(4) = Now
StatusBar.Panels(1) = "WIM-Static Relationship completed."

ProgressBar1.Value = 0

exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
Exit Sub

ErrHandler:
MsgBox "VB Error Number" & Err.Number
StatusBar.Panels(1) = "Error Happened."
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
End Sub

'''=======================================================
''' The 2nd round of comparing
'''=======================================================
Private Sub SecondCompare_Click()
Dim strFileName As String
Dim Source(120) As Integer
Dim IRDerror(3), Kiserror(3), MSIerror(3), ECMerror(3) As Integer
Dim IRDavr, KISavr, MSIavr, ECMavr As Single
On Error GoTo ErrHandler

Dim objApp As New Excel.Application
Dim exBook As Excel.Workbook
Dim exSheet, WimA, StaticA, DBRelation, DBRelation2 As Excel.Worksheet
strFileName = GetExcelFileName("Weigh in Motion", dlg)
Set exBook = objApp.Workbooks.Open(strFileName)

'Set WimMonth = exBook.Worksheets(1)
'Set DBStatic = exBook.Worksheets(2)
Set WimA = exBook.Worksheets(1)
Set StaticA = exBook.Worksheets(2)
Set DBRelation = exBook.Worksheets(3)
Set DBRelation2 = exBook.Worksheets(4)

Dim WeightTime, WimTime, Ratio As Single

ProgressBar1.Min = 0
ProgressBar1.Max = 1000

Dim Timediff As Single
i = 3
j = 4
k = 4
m = 4
A = 0.007 / 86400 '-2.661
B = 137.9 / 86400 '128.6
```

```
'=========================================================
'WIM - Static data relationship, saved in datasheet 4, (-46) <Timediff <(93)
'=========================================================
Do Until StaticA.Cells(i, 1) = ""                          'Compare static data and WIM data
   WeightTime = StaticA.Cells(i, 1) + CSng(CDate(StaticA.Cells(i, 5)))          'Date + Time
   WimTime = WimA.Cells(m, 1) + WimA.Cells(m, 2)
   WimTimeC = WimTime - WimTime * A - B
   'Do Until (WimTimeC > WeightTime - 0.00053)       'Delay average(138)-46 seconds
   Do Until (WimTimeC > WeightTime - 0.00069)        'Delay average(138)-60 seconds
      m = m + 1
      WimTime = WimA.Cells(m, 1) + WimA.Cells(m, 2)
      WimTimeC = WimTime - WimTime * A - B
   Loop
   k = m
RepeatWIM2:
   Do Until (WimA.Cells(k, 4) = 1)                                  'Lane 1: Kistler sensors
      k = k + 1
      If WimA.Cells(k, 1) = "" Then GoTo CompareOver2
      WimTime = WimA.Cells(k, 1) + WimA.Cells(k, 2)
      WimTimeC = WimTime - WimTime * A - B
   Loop

   'If (WimTimeC < WeightTime + 0.00106) Then         '93 seconds
   If (WimTimeC < WeightTime + 0.00116) Then          '100 seconds
      Ratio = WimA.Cells(k, 15) / StaticA.Cells(i, 8)
      If (Ratio > 0.5) And (Ratio < 1.5) Then                  '50% error limitation
         DBRelation2.Cells(j, 1) = WimA.Cells(k, 1) 'date
         DBRelation2.Cells(j, 2) = Format(WimA.Cells(k, 2), "hh:mm:ss")        'Time

         DBRelation2.Cells(j, 35) = WimTime

         DBRelation2.Cells(j, 3) = WimA.Cells(k, 3) 'VHNUM
         DBRelation2.Cells(j, 4) = WimA.Cells(k, 8) 'ca
         DBRelation2.Cells(j, 5) = WimA.Cells(k, 10) ' Speed
         DBRelation2.Cells(j, 6) = WimA.Cells(k, 12) ' TODT
         If WimA.Cells(k - 1, 4) = 0 Then     'IRD
            DBRelation2.Cells(j, 7) = WimA.Cells(k - 1, 15)
         ElseIf WimA.Cells(k - 2, 4) = 0 Then                'Two vehicles may visit these sensors very close to each other
            DBRelation2.Cells(j, 7) = WimA.Cells(k - 2, 15)
         End If
         DBRelation2.Cells(j, 8) = WimA.Cells(k, 15)     'Kistler
         If WimA.Cells(k + 1, 4) = 2 Then                     'MSI
            DBRelation2.Cells(j, 9) = WimA.Cells(k + 1, 15)
         ElseIf WimA.Cells(k + 2, 4) = 2 Then
            DBRelation2.Cells(j, 9) = WimA.Cells(k + 2, 15)
         End If

         If WimA.Cells(k + 2, 4) = 3 Then                     'ECM
            DBRelation2.Cells(j, 10) = WimA.Cells(k + 2, 15)
         ElseIf WimA.Cells(k + 3, 4) = 3 Then
            DBRelation2.Cells(j, 10) = WimA.Cells(k + 3, 15)
         ElseIf WimA.Cells(k + 4, 4) = 3 Then
            DBRelation2.Cells(j, 10) = WimA.Cells(k + 4, 15)
         End If

         DBRelation2.Cells(j, 11) = Format(StaticA.Cells(i, 5), "hh:mm")         'Static time in
         DBRelation2.Cells(j, 12) = StaticA.Cells(i, 6)
         DBRelation2.Cells(j, 13) = StaticA.Cells(i, 8)                          'GVW
         DBRelation2.Cells(j, 14) = StaticA.Cells(i, 9)                          'Tare weight
         DBRelation2.Cells(j, 15) = StaticA.Cells(i, 3)                          'Transaction number
         DBRelation2.Cells(j, 16) = StaticA.Cells(i, 4)                          'Plate number
         DBRelation2.Cells(j, 17) = StaticA.Cells(i, 7)                          'Material source
         DBRelation2.Cells(j, 18) = Format(Ratio - 1, "0.000")                   'Error
         DBRelation2.Cells(j, 19) = Format((DBRelation2.Cells(j, 2) - CSng(DBRelation2.Cells(j, 11))) * 24 * 3600, "##0")
            'Time difference
         DBRelation2.Cells(j, 20) = Format(DBRelation2.Cells(j, 7) / DBRelation2.Cells(j, 13) - 1, "0.000")       'IRD error
         DBRelation2.Cells(j, 21) = Format(DBRelation2.Cells(j, 9) / DBRelation2.Cells(j, 13) - 1, "0.000")       'MSI error
         DBRelation2.Cells(j, 22) = Format(DBRelation2.Cells(j, 10) / DBRelation2.Cells(j, 13) - 1, "0.000")      'ECM error

''          If DBRelation2.Cells(j, 3) = DBRelation2.Cells(j - 1, 3) Then     'Delete repeated records
```

```
''              If Abs(DBRelation2.Cells(j, 18)) > Abs(DBRelation2.Cells(j - 1, 18)) Then
''                  DBRelation2.Rows(j).Delete                                          'Delete the bigger error
''              Else
''                  DBRelation2.Rows(j - 1).Delete
''              End If
''              j = j - 1
''          ElseIf ((DBRelation2.Cells(j, 1) + DBRelation2.Cells(j, 2)) < (DBRelation2.Cells(j - 1, 1) + DBRelation2.Cells(j - 1, 2))) And
j > 4 Then
''              DBRelation2.Rows(j).Delete
''              j = j - 1
''          End If
''
''          If DBRelation2.Cells(j, 14) = DBRelation2.Cells(j - 1, 14) Then
''              If Abs(DBRelation2.Cells(j, 18)) > Abs(DBRelation2.Cells(j - 1, 18)) Then
''                  DBRelation2.Rows(j).Delete
''              Else
''                  DBRelation2.Rows(j - 1).Delete
''              End If
''              j = j - 1
''          End If

            j = j + 1
        End If
    End If
    k = k + 1
    WimTime = WimA.Cells(k, 1) + WimA.Cells(k, 2)
    WimTimeC = WimTime - WimTime * A - B

    If (WimTimeC < WeightTime + 0.00116) Then GoTo RepeatWIM2

ProgressBar1.Value = i
StatusBar.Panels(2) = i
StatusBar.Panels(4) = Now
i = i + 1
Loop
```

CompareOver2:

```
j = 4
Do Until DBRelation2.Cells(j, 1) = ""  'compare static data and WIM data
        On Error Resume Next
        If DBRelation2.Cells(j, 3) = DBRelation2.Cells(j - 1, 3) Then             'Delete repeated records
            If DBRelation2.Cells(j - 1, 15) = DBRelation2.Cells(j - 2, 15) Then
                DBRelation2.Rows(j - 1).Delete                                     'Delete the bigger error
            ElseIf DBRelation2.Cells(j, 15) = DBRelation2.Cells(j + 1, 15) Then
                DBRelation2.Rows(j).Delete

            ElseIf Abs(DBRelation2.Cells(j, 18)) < Abs(DBRelation2.Cells(j - 1, 18)) Then
                DBRelation2.Rows(j - 1).Delete
            Else
                DBRelation2.Rows(j).Delete
            End If
            j = j - 1
        ElseIf DBRelation2.Cells(j, 3) = DBRelation2.Cells(j - 2, 3) Then
            If Abs(DBRelation2.Cells(j, 18)) < Abs(DBRelation2.Cells(j - 2, 18)) Then
                DBRelation2.Rows(j - 2).Delete
            Else
                DBRelation2.Rows(j).Delete
            End If
            j = j - 1
        ElseIf DBRelation2.Cells(j, 15) = DBRelation2.Cells(j - 1, 15) Then
            If DBRelation2.Cells(j - 1, 3) = DBRelation2.Cells(j + 1, 3) Or DBRelation2.Cells(j, 3) = DBRelation2.Cells(j + 1, 3) Then
                DBRelation2.Rows(j).Delete
            ElseIf Abs(DBRelation2.Cells(j, 18)) < Abs(DBRelation2.Cells(j - 1, 18)) Then
                DBRelation2.Rows(j - 1).Delete
            Else
                DBRelation2.Rows(j).Delete
            End If
            j = j - 1
        End If
    j = j + 1
```

```
Loop

'DBRelation2.Cells(8, 24) = ProgressBar1.Value
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
StatusBar.Panels(4) = Now
StatusBar.Panels(1) = "WIM-Static completed."
Exit Sub

ErrHandler:
MsgBox "VB Error Number" & Err.Number
StatusBar.Panels(1) = "Error Happened."
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
End Sub

Private Sub Van_Select_Click()
Dim strFileName As String
Dim Source(120) As Integer
Dim IRDerror(3), Kiserror(3), MSIerror(3), ECMerror(3) As Integer

On Error GoTo ErrHandler
Dim objApp As New Excel.Application
Dim exBook As Excel.Workbook
Dim exSheet, WimMonth, DBStatic, WimA, StaticA, DBRelation As Excel.Worksheet
strFileName = GetExcelFileName("Weigh in Motion", dlg)
Set exBook = objApp.Workbooks.Open(strFileName)
Set WimMonth = exBook.Worksheets(1)                   'WIM
Set DBStatic = exBook.Worksheets(2)                           'Static
Set WimA = exBook.Worksheets(3)                               'Valid WIM data
Set StaticA = exBook.Worksheets(4)                            'Valid Static data
Set DBRelation = exBook.Worksheets(5)                 'Matched WIM-Static data

StatusBar.Panels(1) = "1. Create WIM database..."
StatusBar.Panels(3) = Now
ProgressBar1.Min = 0
ProgressBar1.Max = 1
i = 6
Do Until WimMonth.Cells(i, 1) = ""
i = i + 100
Loop
DataNum.Text = i
i = 3
k = 2
Do Until WimMonth.Cells(i, 1) = ""
   If (WimMonth.Cells(i, 19) = 9) And (WimMonth.Cells(i, 13) = 1) And (WimMonth.Cells(i, 26) > 1380 And WimMonth.Cells(i,
26) < 1480) Then
      k = k + 1
      WimA.Cells(k, 1) = CStr(WimMonth.Cells(i, 2)) 'date
      WimA.Cells(k, 2) = CStr(WimMonth.Cells(i, 4)) + ":" + CStr(WimMonth.Cells(i, 5)) + ":" + CStr(WimMonth.Cells(i, 6)) 'time
      WimA.Cells(k, 3) = WimMonth.Cells(i, 7)                       'Vehicle Number(VHNUM/S)[Station]
      WimA.Cells(k, 4) = WimMonth.Cells(i, 13)          'Lane Number(Ln)
      WimA.Cells(k, 5) = WimMonth.Cells(i, 14)          'Validation variable(Val)
      WimA.Cells(k, 6) = WimMonth.Cells(i, 17)          'Truck/Car Variable(TC)
      WimA.Cells(k, 7) = WimMonth.Cells(i, 18)          'Vehicle classification(CA)
      WimA.Cells(k, 8) = WimMonth.Cells(i, 19)          'Sub-Category(ca)
      WimA.Cells(k, 9) = WimMonth.Cells(i, 20)          'Statistical Category(SC)
      WimA.Cells(k, 10) = Format(WimMonth.Cells(i, 23) * 1.609, "0")                      'Vehicle speed(SPEE) [mile to 1.609344
km/h]
      WimA.Cells(k, 11) = Format(WimMonth.Cells(i, 24) * 0.00305, "0.00")  'Vehicle length(LENG) [0.01 foot to 0.003048 meter]
      WimA.Cells(k, 12) = Format(WimMonth.Cells(i, 26) * 0.00305, "0.00")  'Wheel base[first-last axle](TODT)
      WimA.Cells(k, 13) = Int(WimMonth.Cells(i, 27) * 45.36)               'GVW on P1 (TWT1) [100 pound to 45.3592 kg]
      WimA.Cells(k, 14) = Int(WimMonth.Cells(i, 28) * 45.36)               'GVW on P2 (TWT2)
      WimA.Cells(k, 15) = Int(WimMonth.Cells(i, 29) * 45.36)               'GVW, P1/P2 (TWT3)
```

```
    End If
    i = i + 1
    ProgressBar1.Value = i / DataNum.Text
    StatusBar.Panels(2) = i
    StatusBar.Panels(4) = Now
Loop

i = 3
k = 2
Do Until WimA.Cells(i, 1) = ""
    If WimA.Cells(i, 4) = 1 Then
        k = k + 1
        DBRelation.Cells(k, 1) = CStr(WimA.Cells(i, 2))                    'Time

        DBRelation.Cells(k, 2) = WimA.Cells(i, 10)  'speed
        DBRelation.Cells(k, 3) = WimA.Cells(i + 1, 10)
        DBRelation.Cells(k, 4) = WimA.Cells(i + 2, 10)

        DBRelation.Cells(k, 5) = WimA.Cells(i, 11)  'LENG
        DBRelation.Cells(k, 6) = WimA.Cells(i + 1, 11)
        DBRelation.Cells(k, 7) = WimA.Cells(i + 2, 11)

        DBRelation.Cells(k, 8) = WimA.Cells(i, 12)  'TODT
        DBRelation.Cells(k, 9) = WimA.Cells(i + 1, 12)
        DBRelation.Cells(k, 10) = WimA.Cells(i + 2, 12)

        DBRelation.Cells(k, 11) = WimA.Cells(i, 13)  'TWT2
        DBRelation.Cells(k, 12) = WimA.Cells(i + 1, 13)
        DBRelation.Cells(k, 13) = WimA.Cells(i + 2, 13)

        DBRelation.Cells(k, 14) = WimA.Cells(i, 14)  'TWT1
        DBRelation.Cells(k, 15) = WimA.Cells(i + 1, 14)
        DBRelation.Cells(k, 16) = WimA.Cells(i + 2, 14)

        DBRelation.Cells(k, 17) = WimA.Cells(i, 15)  'TWT3
        DBRelation.Cells(k, 18) = WimA.Cells(i + 1, 15)
        DBRelation.Cells(k, 19) = WimA.Cells(i + 2, 15)

    End If
    i = i + 1
    ProgressBar1.Value = i / DataNum.Text
    StatusBar.Panels(2) = i
    StatusBar.Panels(4) = Now
Loop

StatusBar.Panels(4) = Now
StatusBar.Panels(1) = "Van data selected."
ProgressBar1.Value = 0

exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
Exit Sub

ErrHandler:
MsgBox "VB Error Number" & Err.Number
StatusBar.Panels(1) = "Error Happened."
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
End Sub

Public Function GetExcelFileName(ByVal strTitle As String, cdlg As CommonDialog) As String
  On Error GoTo errProc
    cdlg.DialogTitle = strTitle
    cdlg.Filter = "Microsoft Excel Files(*.xlsx)|*.xlsx"
```

```
    cdlg.DefaultExt = "xlsx"
    cdlg.CancelError = True
    cdlg.ShowOpen
    GetExcelFileName = cdlg.FileName
Exit Function

errProc:
    GetExcelFileName = ""
End Function
Private Sub WimSelect_Click()
'Select all WIM data, build up multiple sheets WIM database

Dim strFileName As String
On Error GoTo ErrHandler
Dim objApp As New Excel.Application
Dim exBook As Excel.Workbook
strFileName = GetExcelFileName("Weigh in Motion", dlg)
Set exBook = objApp.Workbooks.Open(strFileName)

StatusBar.Panels(1) = "1. Create WIM database..."
StatusBar.Panels(3) = Now
ProgressBar1.Min = 0
ProgressBar1.Max = 1

For k = 1 To 16 '16 worksheets
i = 3
Do Until exBook.Worksheets(k).Cells(i, 1) = ""
    If (exBook.Worksheets(k).Cells(i, 14) = 9999) Or (exBook.Worksheets(k).Cells(i, 23) = 0) Or (exBook.Worksheets(k).Cells(i, 24)
= 9999) Then
        exBook.Worksheets(k).Rows(i).Delete
        i = i - 1
    End If
    i = i + 1
    StatusBar.Panels(2) = k
    StatusBar.Panels(3) = i
    StatusBar.Panels(4) = Now
Loop
exBook.Save
Next k

exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
StatusBar.Panels(1) = "Create WIM database finished."
StatusBar.Panels(4) = Now
Exit Sub

ErrHandler:
MsgBox "VB Error Number" & Err.Number
StatusBar.Panels(1) = "Error Happened."
exBook.Save
exBook.Close
Set objApp = Nothing
Set exBook = Nothing
Set exSheet = Nothing
End Sub
```

C.3 Statistical Analysis for Heavy Trucks at the Landfill Site

C.3.1 Introduction

The static weight data from January to September 2009 used to investigate variability in gross and tare weights of trucks for classes 6, 7 and 10 (CL-6, CL-7 & CL-10). The analyses show that mean of gross and tare weights vary in the range of ±10% and ±1% respectively. The numbers of trucks observed in this period (see "Count" columns) demonstrate big enough sample sizes for proper conclusions about the trucks' weight data. This information can help:

- Find other license plates in each group (e.g. WM classes 6, 7 and class 10);
- Track the trucks of each group in the corresponding WIM data.

In Table C. 4, Table C.5, Table C. 6, Table C. 7 and Table C. 8 the means of tares and gross weights are between the rounded down min and rounded up max observed during the period of analyses.

C.3.2 Waste Management (WM) Garbage Trucks

WM trucks are divided into 4-axle (Figure C. 2) and 3-axle trucks (Figure C. 3). All WM trucks, which travel over the WIM system, have to be classified as class 6 since the 4-axle trucks travel over the WIM site with the middle axle in up position.

Table C. 4- Tare and GVW weights for the "WM-Class 6"

Plate	Count	GVW			Tare		
#	2910	Round Dw	μ	Round Up	Round Dw	μ	Round Up
1451TP	191	14500	19750	25500	13500	13977	14500
1513CL	0						
1516CL	0						
1530TP	303	15000	22316	27500	14500	15154	16000
3547KV	90	17000	23244	28000	15500	15839	16500
3548KV	201	16500	22579	28000	15500	15838	16500
3549KV	16	16500		25000	15500		16500
3550KV	256	16500	23360	27500	15500	15847	16500
3553KV	176	16000	22534	28500	15500	15887	16500
3554KV	140	16500	23631	28500	15500	16049	16500
3555KV	23	17000	19804	26500	15500	16226	17000
3592KV	171	14500	21095	26500	13500	13754	14000
3969NZ	238	14500	21303	26500	14000	14445	15000
4388WX	82	17000	24056	28500	16000	16298	17000
4422ME	119	14500	19851	25500	13500	14004	14500
4423ME	219	14500	20941	27500	13500	13924	14500
5497XC	182	16000	22183	28500	15500	16051	16500
5967LR	12	20500		26000	16000	16373	17000
6170LJ	120	17500	23767	28500	15500	15908	16500
8775ML	150	16000	23259	28000	15500	16058	16500
9613NE	221	15500	21566	27500	14000	14560	15000

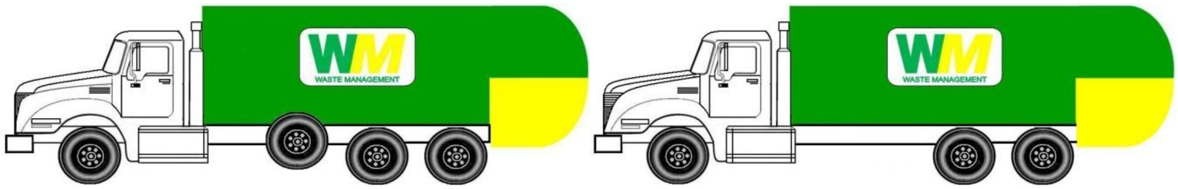


Figure C. 2- WM garbage truck (3 & 4 axles, Classes 6 & 7, FHWA) at the Landfill site

Therefore over the WIM site, the most important difference between these trucks is that a 4-axle truck has normally heavier gross and tare weights than a 3-axle. The tare and GVW means within their minimum and maximum data observed for the WM-Class 6 garbage trucks are shown in Table C. 4.

The final means for each truck's GVW and tare weights are weighted means calculated for the months January to September 2009. Since most of the population sizes are greater than 30, the means are reliable and can be considered as the expected values. The confidence intervals were also calculated considering the total number of trucks during this period. The frequency analysis of tare weights in the WM-class 6 garbage trucks show that the tare weights for these trucks can be categorized in two levels including (**13.500-15.000**) and (**15.500 to 16.500**) tons (Table C. 9).

Table C.5- Tare and GVW weights for the "WM-Class 7" (4^{th} axle in up position)

Plate	Count	GVW			Tare		
#	2867	Round Dw	µ	Round Up	Round Dw	µ	Round Up
1474TP	17	19500	51147	64000	17500		20000
1474TP	87						27000
4384WX	286	21500	28065	32000	20000	20695	23000
4385WX	277	21000	27756	32500	20000		23000
4386WX	258	21000	28060	32500	20000	20703	23500
4387WX	277	21000	27856	33000	20000		23500
4432WX	155	20500	27453	31500	20000	20555	22000
4460WX	192	20500	27767	31500	20000	20660	23000
4461WX	263	21500	27505	33000	20000		24500
4462WX	317	21500	28016	32500	20000	20916	23000
4482WX	344	21500	28042	32500	20000	20927	23000
4910LW	69	19000	23544	28500	16500		20500
7225WR	211	21500	27469	32000	20000		23500
8119XX	0						
8120XX	0						
8198RS	75	16000	21878	29500	16000		20000
8976JL	19	19500	23566	27500	17500	18994	20500
9160XV	20	23000	28535	32000	20000		21500

The means of tares and gross weights within their minimum and maximum data observed for the WM-Class 7 garbage truck are shown in Table C.5.

The final means for each truck's GVW and tare weights are weighted means calculated for the months January to September 2009. Since most of the population sizes are greater than 30, the means are reliable and can be considered as the expected values. The confidence intervals were also calculated considering the total number of trucks during this period. The frequency analysis of tare weights in the WM-class 6 garbage trucks show that the tare weights for these trucks can be categorized in the level of (**20.000 to 23.500**) tons.

The means of tares and gross weights within their minimum and maximum data observed for the "Other-Class 6" and "Other-Class 7" garbage trucks are shown in Table C. 6 and Table C. 7. Tables show that it is difficult to find ideal categories for these trucks.

The means of tares and gross weights within their minimum and maximum data observed for the Class 10 garbage trucks (Figure C. 4) illustrates that the tare weights for these trucks can be categorized in the level of (**22.000 to 25.000**) tons (Table C. 8).

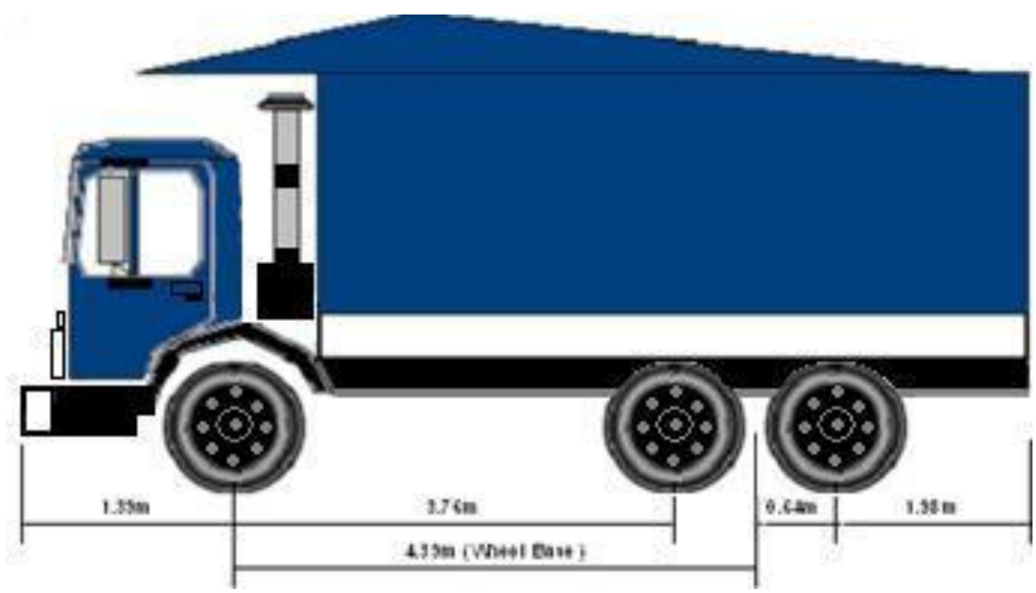


Figure C. 3- Garbage truck (FHWA, 3-Axle Class 6) at the Landfill site

Table C. 6- GVW and tare weights for the “Other Class 6” garbage trucks

Plate #	Count 5545	GVW			Tare		
		Round Dw	µ	Round Up	Round Dw	µ	Round Up
1622KE	6	12500	16043	22000	12000	13200	14500
2206KP	0						
2314RB	2						
2322TE	62	19500	25406	28500	16000	16487	17000
2577RZ	39	17000		37500	16500		19500
2650RP	1						
3118RW	134	15000		35000	14000		18500
3250RE	118	13500	17416	24500	12500	12959	13500
3545KV	191	16500	22557	31500	15000	15662	16500
3552KV	145	16000	22338	27000	15000	15677	16500
3956NR	858	18000	22516	26000	17500		19500
3956NZ	0						
4519WX	1279	17000	22053	31000	17000	17405	18500
5304DV	88	18500	25983	31000	16500	16807	17500
5474VN	50	15500	22355	28000	15500	16880	19000
5500RM	0						
5524TZ	10	14500	15089	16000	13500	13701	14000
5525TZ	13	15000		19500	13000		14000
5807WL	1038	17500	21834	28500	17000	17738	18500
5828TA	91	19500	24404	28500	16500		18000
5832VM	7	18500	23088	28500	16500		17500
6001NZ	71	15000	19852	32500	14500		18000
7770TC	1053	17500	21872	26500	17000	17820	19000
7908WZ	124	15500		38500	14000		17000
8001VM	19	19000		37000	16500		20500
8055XX	0						
8151RS	54	18500	23426	30500	17000		21500
8743XN	0						
8841HR	0						
9049KD	1						
9492VT	0						
9512VT	45	18500	22795	31500	16500		19000
9512VT	5				20000		25000
9519ML	41	18000	21249	26000	16500	16850	17500
9724WY	0						

C.3.3 Results

The tare weight analyses shows that the WM-CL6, WM-CL7 and CL10 trucks can only be tracked in the static data by frequency analyses (blue color in Table C. 9). In each interval, there are plate numbers that should be omitted in order to gain accurate justifications in each category. The analyses show that in the WM class 6 garbage trucks, the difference between tare weights cannot exceed 1500 kg (Table C. 9).

Table C. 7- GVW and tare weights for the "Other Class 7" garbage trucks

Plate #	Count 183	GVW			Tare		
		Round Dw	µ	Round Up	Round Dw	µ	Round Up
1635TV	4	17500	20290	23000	17000	17475	18000
2808XS	27	16000	22081	28500	16000		19000
3224TP	3	16500	18043	20000	12500		13000
3395VC	0						
3536WV	1						
4387WP	37	17500		35500	17000		18000
4387WP	46				19500		21500
7745TC	35	18000	22975	28000	16500		18500
7745TC	20				17000	18591	20000
8170MY	1						
8436VP	2						
8479ML	4				16000		18000
8479ML	3	18500		27000	19000		20000

Table C. 8- GVW and tare weights for the "Class 10" garbage trucks (FHWA, 6-Axle)

Plate #	Count 2298	GVW			Tare		
		Round Dw	µ	Round Up	Round Dw	µ	Round Up
4616VJ	0						
4920WT	0						
6079LN	145	22000		58000	19000		21500
6079LN	161				22500		23500
6079LN	66				23500		26000
6080LN	455	20500	46603	60000	22000		24000
6335VF	0						
7905WJ	47	30500	47034	59000	15000		17000
7905WJ	8				19000		21000
7905WJ	560				22500		25000
7982YB	0						
8977YB	0						
8978YB	0						
8982YB	0						
9470RE	50	20000	46701	60000	15000		17000
9470RE	121				19000		21000
9470RE	195				22500		24000
D1911W	0						
WP1475	490	25500		61500	22000	23312	24500

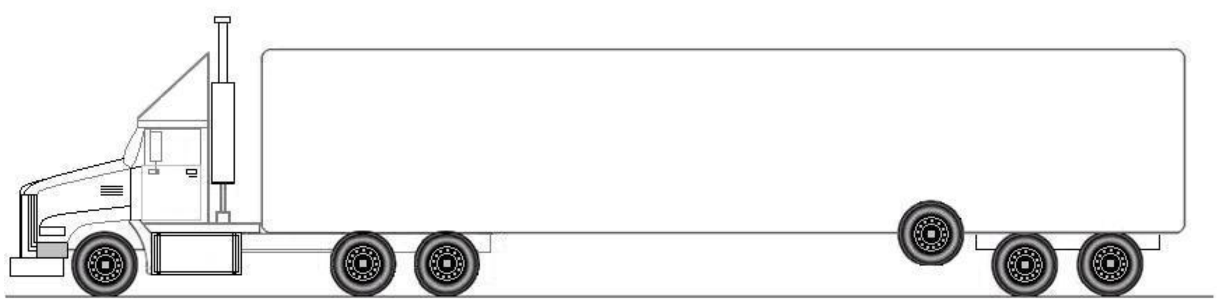


Figure C. 4- Garbage truck (FHWA, 6 & 7 axles, Class 10) at the Landfill site

Table C. 9- Tare weight analysis of garbage trucks at the Landfill site

Tare Weight Analysis								
Tare Intervals		WM-CL6	WM-CL7	Other-CL6	Other-CL7	CL10	Exception	Comments
11000	13000	-	-			-		
13000	15000							
13500	15000						Other CL-6: 1622KE,3118RW,5524TZ,5525TZ,6001NZ,7908WZ	WM CL-6
15000	17000							
15500	16500						Other CL-6: 2322TE,3118RW,3545KV,3552KV,5474VN,6001NZ,7908WZ & Other CL-7: 2808XS, 7745TC, 8479ML & CL-10: 7905WJ,9470RE	WM CL-6
15500	17000							
17000	19000							
16500	19500							
16000	20000							
19000	21000							
21000	23000							
20000	23500						Other CL-6: 9512VT & Other CL-7: 4387WP & CL-10: 6079LN,6080LN,7905WJ,9470RE,WP1475	WM CL-7
23000	25000							
22000	25000						Other CL-6: 9512VT & WM CL-7: 1474TP, 4384WX, 4385WX, 4386WX, 4387WX, 4460WX, 4461WX, 4462WX, 4482WX, 7225WR	CL-10
25000	27000							

Possibility of weight interval occurrence for the class
Common weight interval between classes
The weight interval justified for the specific class

Appendix D

Manual Calibration Sheets

The Manual Calibration Sheet is a procedure designed for the MS-WIM systems at the CPATT experimental sites. The procedures assist WIM users to recalibrate a WIM system in a very time and cost effective procedure. This procedure also enables the WIM users to recalibrate a WIM system by allocating only one operator in almost all of the full recalibration efforts of a system. In the **Manual Calibration Sheet,** a guideline exists for assisting the operators at WIM sites to use the sheets efficiently.

D.1 Steps for WIM Sensor Recalibration (Individual Sensor System Adjustments)

There are three steps to check the sensors' calibration status as follow:

1. **Select the Sensor Set and Enter the Test Vehicle information in the "Manual Calibration Sheet"**

   At the Top Left of the **Manual Calibration Sheet** there is a place to enter information about the WIM user's test vehicle such as distance or weight information. As soon as the user inputs the information in any of major international unit format (SI or Imperial) the other format in the adjacent cell will be filled. For instance, by entering 5.9 m in the cell **C2**, 1937.5 (in the format of 100ft) will be shown in the cell **C4**.

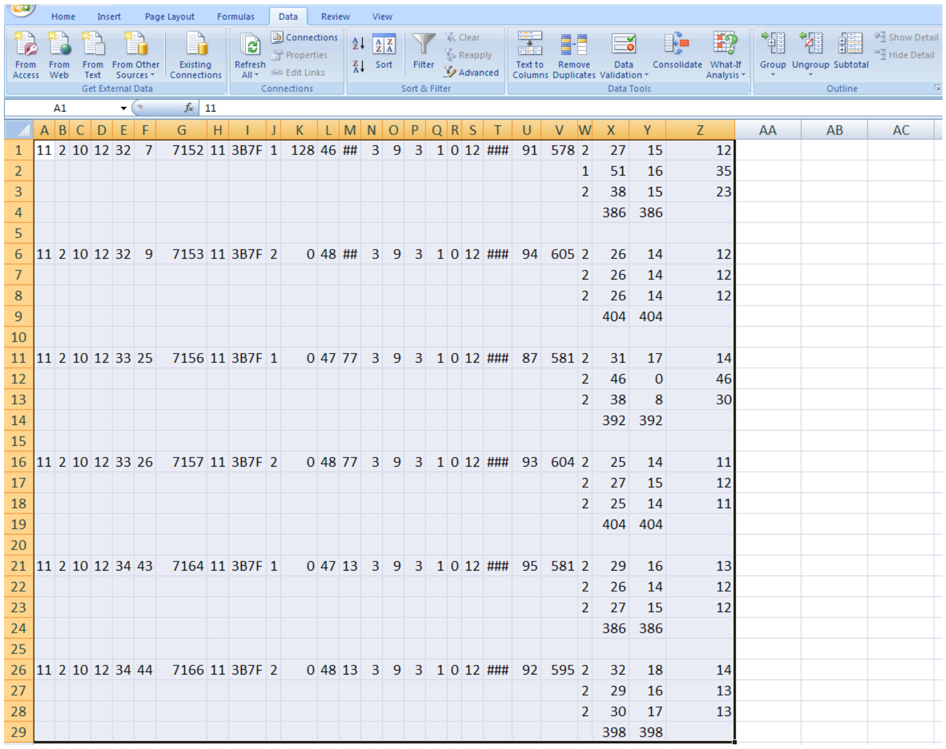
Unit	Veh.	LENG	Bum-1st	TODT	GVW	Drive Ax	2nd	3rd	4th	Gas	Air ^{0}C	Weather	Road
SI	F150	5.9	0.6	3.7	2685.0	1530.0	1155.0						
		590.6	60.0	366.5	26.9	15.3	11.6						
US		1937.5	196.9	1202.5	59.2	33.7	25.5						

2. **Record the Path Run (1 to 3 according to 3.1.3.3) and Speed and Drive the Test vehicle over the WIM System**

Drive two sets each set less than or equal to five times over the WIM system.

3. **Data Entry**

Copy and paste the real traffic WIM data into a blank Excel sheet and use **Data, Text to Column** for changing it to text format. The data after changing to format will be such as in Figure D. 1.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	11	2	10	12	32	7	7152	11	3B7F	1	128	46	##	3	9	3	1	0	12	###	91	578	2	27	15	12
2																							1	51	16	35
3																							2	38	15	23
4																								386	386	
5																										
6	11	2	10	12	32	9	7153	11	3B7F	2	0	48	##	3	9	3	1	0	12	###	94	605	2	26	14	12
7																							2	26	14	12
8																							2	26	14	12
9																								404	404	
10																										
11	11	2	10	12	33	25	7156	11	3B7F	1	0	47	77	3	9	3	1	0	12	###	87	581	2	31	17	14
12																							2	46	0	46
13																							2	38	8	30
14																								392	392	
15																										
16	11	2	10	12	33	26	7157	11	3B7F	2	0	48	77	3	9	3	1	0	12	###	93	604	2	25	14	11
17																							2	27	15	12
18																							2	25	14	11
19																								404	404	
20																										
21	11	2	10	12	34	43	7164	11	3B7F	1	0	47	13	3	9	3	1	0	12	###	95	581	2	29	16	13
22																							2	26	14	12
23																							2	27	15	12
24																								386	386	
25																										
26	11	2	10	12	34	44	7166	11	3B7F	2	0	48	13	3	9	3	1	0	12	###	92	595	2	32	18	14
27																							2	29	16	13
28																							2	30	17	13
29																								398	398	

Figure D. 1- Data Entry

4. Data Input to the Manual Calibration Sheet

Copy the data from the step 1 and paste it into cell **AA32** of the **Manual Calibration Sheet**. The data will automatically sits into cells **A32** to **Z63**. After driving 10 times over the sensors, the final recommended calibration factors (CI) for P1 and P2 will be shown in the cells **L11** and **L12**. The new CIs are displayed in the red if they are significantly different from the default values. Otherwise, the cell values are shown in the blue (Figure D. 2).

5. Do the whole test for additional two runs (20 drives over the sensors)

By driving up to 20 times over the sensors and repeat the steps 3 and 4, the final recommended calibration factors (CI) for P1 and P2 will be shown in the cells **L19** and **L20** and in the cells **L25** and **L26** . The new CIs are displayed in the red if they are significantly different from the default values (Figure D. 3).

6. Take Final 5 Drives

The final 5 drives will help decide whether the factors are correctly adjusted.

7. Change the Path Run and Speed if required

Information such as temperature, climate condition, gas tank of test vehicle, date and time of test, etc. can be recorded in each sheet for future analyses.

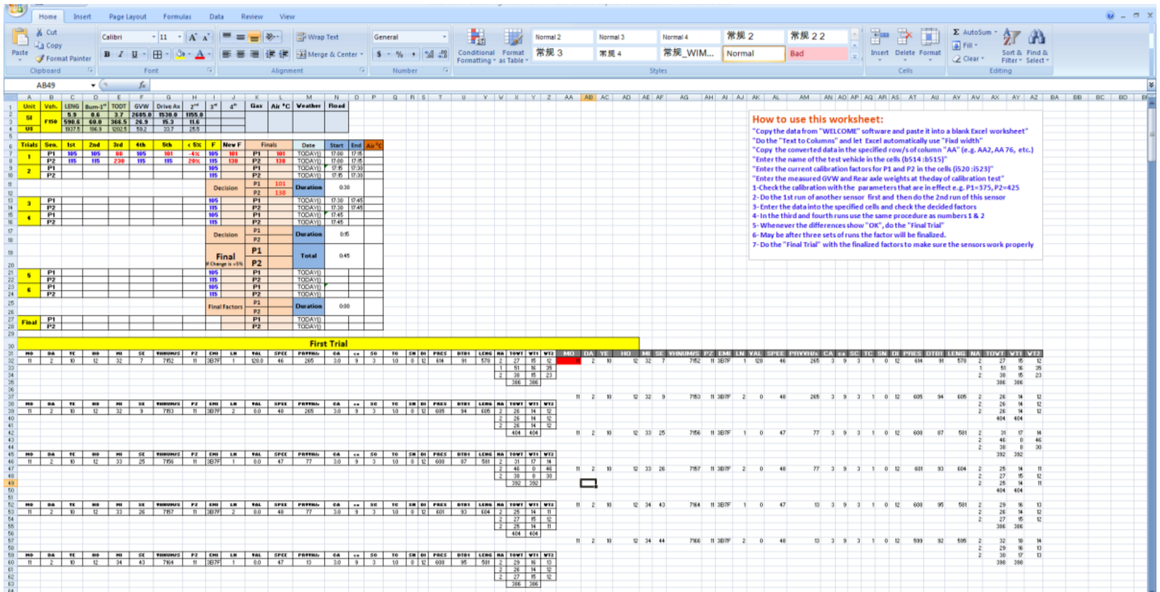


Figure D. 2- Data Input in the **Manual Calibration Sheet** in the cell **AA32** (the red box)

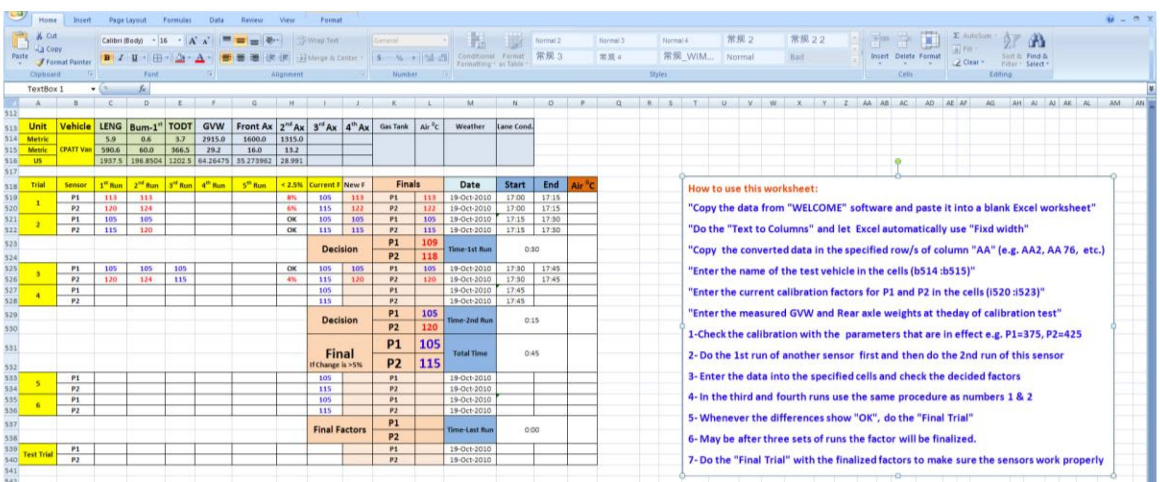


Figure D. 3- Adjustment of CIs for the quartz sensor at the Landfill Site (six drives)

D.2 Steps for MS-WIM Station Recalibration

MS-WIM systems can also be recalibrated in just one **Manual Calibration Sheet** per lane, by driving over the system and use the sheet for deciding about the individual sensors' CIs. There are different tables for every sensor system, which will display the recommended CIS separately. Figure D. 4 demonstrates the **Manual Calibration Sheet** designed for the MS-WIM system at the Highway 401 site including quartz and polymer piezoelectric sensor systems.

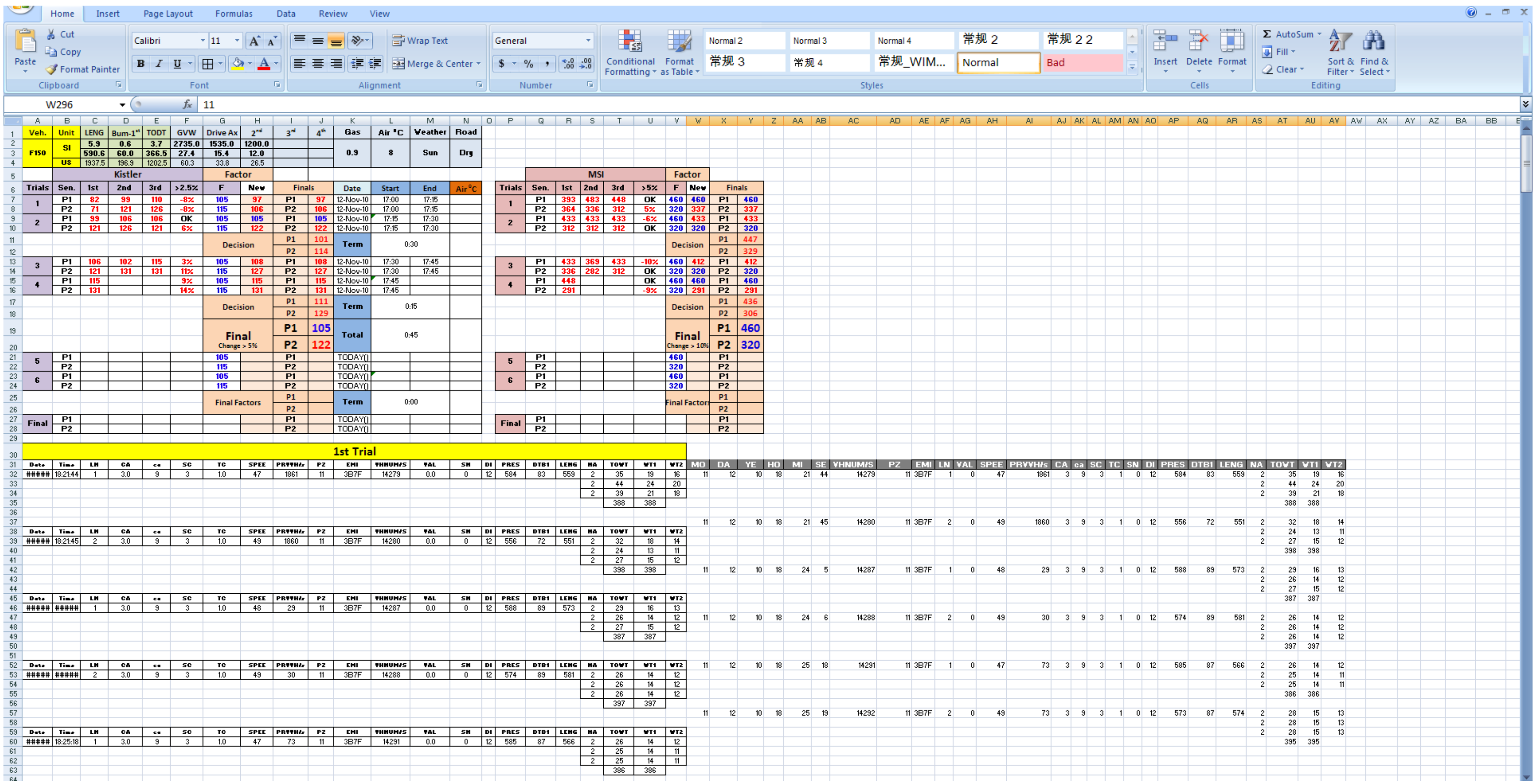


Figure D. 4- Recalibration of the MS-WIM system, one **Manual Calibration Sheet** per lane